PROPERTIES OF MANCOS SHALE SOILS AND EFFECTS ON PLANT COMMUNITIES

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Final Report

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INTRODUCTION

Geological History of Mancos Shale

In the last several years there has been an increase in coal and uranium strip-mining activity in the Colorado Plateau region. The heightened activity, the concurrent development of legal requirements for the revegetation of strip-mined land, and the exploration of the energy potential in "oil shales", have led to an interest in the composition and properties of the shale formations which are frequently associated with coal and uranium deposits. Spent shales, which are the debris of ore processing, and overburden shales, which have been removed to expose energy-bearing formations, have often been used in an attempt to revegetate spoil or overburden dumps at mine sites. However, many of these shales, when exposed and weathered in naturally occurring outcrops, present physical and chemical characteristics that inhibit the successful establishment of vegetation which would normally be found in the area. The needs of the mining industry have sparked interest in the determination of shale characteristics which affect vegetation, and in experiments for the treatment and amendment of shales to reduce the inhibitive effects on vegetation.

One shale formation commonly associated with energy-rich deposits in the Colorado Plateau is the Mancos, a Cretaceous-aged, marine shale. For the purposes of this study, the Mancos formation is defined as the stratigraphic interval between the top of the Dakota sandstone and the basal sandstone of the Mesa Verde formation or its equivalent (Wimer 1969). The major factors in

Mancos which seem to affect present patterns of plant distribution were determined to some degree by the environment in which the shale was formed, and by the geologic processes which have affected it since that time. During the 65 million years of the Cretaceous period, the area of the Rocky Mountain geosyncline was repeatedly inundated by a shallow sea. Accumulation of the fine sediments from erosion of the almost continually rising Highlands to the west led to the formation of the Cretaceous marine shales. Weathering and erosion of the Highlands resulted in deposition of sand along the western shoreline; the finer clay particles were carried farther east before settling to the sea bottom. Receding seas left sand deposits at each new shoreline, overlapping what had been offshore clay deposits. A reinvading sea deposited fine silts and clays on top of older sandstones. The Mancos was deposited, therefore, with many thin sandstone beds projecting into it (Dunbar 1960). At some sites where Mancos is presently exposed it has weathered with interfingered sandstones and has produced a soil of different texture and potential for successful establishment of vegetation than that exposed and weathered at sites with little or no adjacent sandstones.

Following the Cretaceous epoch, the Cenozoic era was a period of mountain formation. With the uplift of the Rocky Mountains, the northern and eastern extensions of the Mancos formation were subjected to intense pressures of folding and faulting. The affected shales, and those modified by intrusive activity in local sites, contain an increased percentage of illite. The areas of Mancos unaffected by high heat and pressure are

composed primarily of montmorillonite, or randomly stratified illite-montmorillonite clays.

Various aspects of the chemical make-up of Cretaceous shales have been described. Pliler and Adams (1962) ascribed the uniform distribution of some minor elements throughout the Mancos to the deposition of the sediment in a shallow sea. The constant reworking and mixing of the sediment resulted in a homogeneous distribution of biologically inactive compounds and particulate matter in the Mancos. When Stevenson (1960) compared the organic composition of terrestrially and aquatically derived shales he found an increase in the organic content of the latter. Aquatic systems function as organic sinks, as material which is deposited may have little opportunity to be recycled. Tourtelot (1964) emphasized the role of small amounts of organic carbon in shales in determining the redox potential and thus the microenvironment and microorganisms which develop in an area. Biologically active compounds can be redistributed by the various organisms adapted to each microenvironment. There are two processes by which elements could have been included in the shales: 1) a quantity of the element could be adsorbed onto a clay particle as it was eroded or deposited, and 2) sorption of the element could occur during diagenesis (the process of rock formation from sediment). Tourtelot (1964) cites sorption as the process most strongly affecting minor element composition in shales. The process continues until diagenesis is complete, whether or not equilibrium has been reached. This can account for varying chemistries in rocks affected by the same forces of creation.

Shales are clastic sedimentary rocks formed by the deposition and cementing together of clay minerals. The particles are the product of mechanical and chemical weathering of rocks and are transported by wind, water, ice, or gravity to be left in a new location. The sediments are cemented together under pressure and shales are formed. They may be formed of a variety of clay minerals. The two silicate clays which are principally involved in Mancos shale are illite and montmorillonite. The amount and type of clay mineral present in the shale influences the physical and chemical properties of the soil that eventually forms from the shale and therefore affect the success of vegetation on the soil. Clay particles are crystalline. The montmorillonite group of clay-crystals are composed of a 2:1 type crystal lattice. Each crystal unit is three-tiered and consists of an alumina layer (Al,O,OH) tightly held between two silica (Si,O) layers. The units are held together by weak oxygen-oxygen bonds. There is little attraction between the oxygens at the bottom of one crystal layer and the top of the next, so the space between the layers is expandable. Because the crystal lattice expands without difficulty, water molecules and cations can move easily between the crystal units. By this means montmorillonite has a very large internal surface area which is, like the external surface, negatively charged. The clay has a high cation-adsorption capacity, plasticity, and cohesion. It shrinks to a great extent on drying. Illite is another clay mineral associated with marine shales and it also has a 2:1 crystal lattice with each crystal unit composed of two layers of silica and one of alumina. Illite particles are

typically larger than montmorillonite. About 15% of the silica (+4) in its silica sheets has been replaced by aluminum ions (+3). The valence difference is balanced by the addition within the unit of potassium ions (+1). The potassium ions fit between the structural units, binding them together more strongly than the montmorillonite units are bound. Therefore, illite is much less expandable, less plastic, with less available active internal surface area and lower cation exchange capacity than montmorillonite (Buckman and Brady 1969).

Physical-Chemical Properties of Shale and Shale-derived Soils

The chemical and physical characteristics of Mancos have been determined by its geologic history. As a result of its formation in a marine environment, the Mancos has a high content of sodium and sulfate. The influence of variable amounts of organic matter and calcium carbonate affect the weathering pattern of exposed shale, and the physical and chemical make-up of shale-derived soils. Mancos soils have a high clay content, generally including a high percentage of expandable clays. The soils swell on wetting and often exhibit poor water penetration. High concentrations of sodium in the crystal lattice exaggerate this condition. Desiccation cracks form as the soil dries, concentrating soil gases in the cracks and decreasing soil aeration. The occurrence of occasional sandstone nodules and interbedded sandstone members of the Mancos modify the fine texture which attains as the shales are physically broken down. The presence of sand improves water penetration and aeration in the

shale-derived soil.

Two physical characteristics of Mancos-derived soils have been studied in relation to their effect on vegetation: 1) expansion of the clay on wetting, and 2) the compactability of the fine-textured soil. White (1962), working on the Pierre formation, another Cretaceous marine shale, measured clay expansion on wetting in the soil as changes in soil elevation and the arrangement of pore spaces. The total amount of pore space in the soil did not change, but the distribution of space changed on drying from predominately pores to desiccation cracks. The rearrangement decreased aeration in the soil by concentrating soil gases in the cracks. The stress on root systems was greater when cracks formed. The soil material did not expand uniformly on wetting. The microrelief, the desiccation cracks, and the areas of root stress were continually rearranged. Adams and Hanks (1964) measured the moisture lost from shrinkage cracks which have 2.9 to 4.6 more surface exposed on the vertical crack walls than on the horizontal surface per square yard of surface soil. In addition, a clay soil in an arid environment loses more moisture by evaporation from the surface than a sandy soil. The fine clay allows capillary movement of soil water to the surface (Walther 1973). Soil compaction also reduces soil oxygen concentration and the rate of root growth (Gill and Miller 1956). Roots which can expand somewhat against increased mechanical pressures at normal oxygen levels cannot grow at the same pressures with decreased oxygen levels. Some types of vegetation, specifically the species with deciduous cortices, are less affected by soil compaction (White

and Lewis 1969). Transport tissues of the roots are able to expand into the area left by the disintegration of the cortex and are not destroyed by compacting soil. Species with horizontal root systems are more susceptible to damage by the formation and rearrangement of desiccation cracks. Root elongation is sensitive to aeration because the rate of oxygen consumption (respiration) is greatest at the root tips which are undergoing cell division at a very high rate. Oxygen consumption decreases with distance from the root tip (Black 1968). Roots extend by pushing aside soil particles to expand pore spaces (Wiersum 1957). Roots in clay soils, with smaller pore spaces, can only succeed if they can push the clay particles aside, a feat more easily accomplished in a wet soil than in a dry one.

The chemical content of Mancos determines the weathering process the shale undergoes. Variable amounts of organic debris and calcium carbonate ($CaCO_3$) are laid down in the shale along with high concentrations of sodium and sulfur. On exposure to air and water, organic sulfur in the shale is converted to sulfuric acid (H_2SO_4), and cations are slowly released from the clay lattice. Black (1968) described three types of substances which will replace exchangeable sodium on a clay: 1) soluble calcium salts, such as gypsum ($CaSO_4$) formed from the sulfuric acid present in some weathering Mancos, and releasing sodium sulfate (Na_2SO_4) to the soil solution; 2) sulfuric acid or iron sulfate ($FeSO_4$), products of anaerobic bacterial activity, may be adsorbed on the clay, again releasing Na_2SO_4 to the soil solution; and 3) calcium or magnesium carbonate ($MgCO_3$), present in high concentrations

in some Mancos shales, and resulting in the release of Na_2CO_3 into the soil solution. The above exchanges would produce a calcium-saturated clay, and a sodium salt in the soil solution.

Where the weathering process is not progressing, or where insufficient calcium is available to be adsorbed onto the clays, sodium-saturated clay soils create specific problems for vegetation. The monovalent ions exhibit a strong tendency for separation of single colloids because there is little opportunity for interparticle bonding, and there is a greater force of repulsion between like-charged particles. The particles do not flocculate, but remain dispersed in soil solution. Soil pores remain small and aeration is inhibited. In addition to the swelling capability of the montmorillonite clay unit, imbibition of water by sodium increases its volume per gram (Black 1968). Sodium sulfate in soil solution within the root zone creates a high osmotic potential against which roots must compete for water. The dispersion of sodium-saturated clays often causes surface sealing on wetting, which greatly reduces the infiltration of water (Power et al. 1978).

Sample Collections

One hundred twenty bedrock samples of Mancos shale were collected from various outcrops in Arizona, Utah, Colorado, and New Mexico. The collection sites are shown on Fig. 1. Samples were selected to exclude obviously sandy, silty, or calcareous lithologies, so the sample suite represents the shaley components of the Mancos formation. In Fig. 1 are shown also the locations

of the five areas selected for detailed soil chemistry and vegetation studies. A total of 123 soil samples were collected from these locations and analyzed by procedures described below.

The Mancos Shale Problem

The regions of Mancos shale are relatively barren of vegetation. In addition, coal strip-mining operations cause existing local lithologies to become covered by Mancos surficial debris, and these, too, support little vegetation. The long history of mining in the Colorado Plateau and the recent development of technology for massive strip-mining have resulted in extensive areas of the land being left in a state of disturbance which is requiring a major effort of stabilization and revegetation. The ever-increasing demands for more energy and increased mining is currently intensifying the problem. Federal and state regulatory policies designed to assure that mining companies will restore the land to a natural state are not always formulated with a complete awareness of the ecological problems of converting a new bare area to a stable vegetation resembling the original vegetation of the area. In a region where precipitation is not only an important limiting factor but is notoriously sporadic and unpredictable in timing and amount and where the "soil" material is frequently high in silts and clays which tend to be saline and alkaline in nature, recovery is a slow process. Even when exposed at the surface under natural conditions Mancos shale often represents one of the most extensive areas barren of vegetation. In the same physiography and climate, however, other strata

successfully support a vegetation representative of the regional climate. The results of this study are applicable on a widespread regional basis from Canada to Mexico and to both reclamation and grassland productivity.

In the uranium industry, shale may play a multiple role. Mill tailing ponds should be separated from the water supply below by an impervious layer. A shale having a high percentage of montmorillonite and high sodium concentration would be ideal to seal off the bottom of such ponds. By crushing, wetting, and compacting an impervious layer could be formed. A second use would be as an impervious seal across the top of abandoned tailing piles. Such a layer would cause precipitation to drain off, maintain a protective cap, and provide an impenetrable barrier to the growth of roots of vegetation in a reclamation program. If vegetation were to be grown on the surface layers of shale, it is essential that the factors inhibiting plant growth be known so that corrective measures could be taken.

The features of Mancos shale which might reasonably inhibit plant growth are several. The ratio of montmorillonite to illite is important in the chemical composition as well as the effect on physical characteristics of swelling and contraction, infiltration of water, aeration, and the development of soil structure. Compaction and sealing inhibit oxygen exchange and divert precipitation from infiltration to runoff. High sodium values may not only be osmotically toxic but prevent the necessary flocculation and development of soil structure. High concentrations of sulfur compounds such as iron sulfide when moistened may use up critical

amounts of soil oxygen by the oxidation resulting in iron sulfates. The oxygen deficiency impairs root respiration. Hydrolysis to sulfuric acid results in the lowering of pH values to inhibitive conditions but does make some ions more soluble, including iron. The acidity may be somewhat ameliorated by the conversion of calcium carbonate, if abundant, to calcium sulfate. The latter is often found as crystals and soil solutions may become saturated with gypsum, which would limit the plants on these soils to gypsiphilic species. High concentrations of calcium in the soil could result in the substitution of calcium for sodium on the exchange sites of the clay particles, freeing the sodium to form sodium sulfate.

A good review of previous classifications and factors affecting distribution of salt desert shrubs in the United States is that of Branson, Miller, and McQueen (1967). For the species discussed in our study, they ranked them as follows in increasing order of salt tolerance based on osmotic stress (atmospheres) at field capacity: blue grama grass (<u>Bouteloua gracilis</u>), big sagebrush (<u>Artemisia tridentata</u>), horsebrush (<u>Tetradymia spinosa</u>), shadscale (<u>Atriplex confertifolia</u>), alkali sacaton (<u>Sporobolus airoides</u>), galleta (<u>Hilaria jamesii</u>), western wheatgrass (<u>Agropyron smithii</u>), and Nuttall saltbush (<u>Atriplex nuttallii</u>) which is physiologically similar to mat saltbush (<u>Atriplex corrugata</u>). The same authors, Branson, Miller and McQueen (1970) provided an ecological study of the relationship of vegetational communities to shale-derived soils in northeastern Montana, which is outside the range of Mancos shale. One of the most complete hydrologic-biotic studies in Mancos shale is from the Badger Wash Basin in western Colorado

(Lusby, et al. 1963). One of the most complete environmental-vegetational studies is that of Shantz and Piemeisel (1940) in the Escalante Desert at the western edge of the Mancos shale.

Objectives

The specific objectives of the first phases of this study were as follows:

1. To examine the natural variations of selected aspects of the lithology and chemistry of Mancos shale on a regional basis. These characteristics were to be derived from a combination of field studies and detailed laboratory geochemical analyses.

2. The shale analyses were to be correlated with phytosociological gradients of density, coverage, and biomass of the dominant species and community types, with especial attention to the limits of distribution.

3. The correlation of physical-chemical parameters to plant distribution were to provide hypotheses of limiting factors to plant growth, which in later continuing studies will be tested by experimental manipulation, both chemical and physical, of the shale.

METHODOLOGY

Analytical Methods

Clay Mineralogy

Samples of Mancos shale were crushed, dispersed in water and washed free of salt by centrifugation. The <2μ particle size was separated by centrifuge and aliquots were evaporated to dryness at 110°C on glass slides to prepare oriented samples for X-ray diffraction analysis. The latter was performed by means of a General Electric XRD-5 equipped with a copper tube. The angular range $2\theta = 50$ to 2° was recorded. The samples were solvated with ethylene glycol, using the vapor saturation method at 60°C, and the X-ray pattern was again recorded. Estimation of the qualitative clay composition of the samples was based on standard interpretation procedures (Brown 1961) for the simple clay minerals. Mixed-layered or interstratified clays were quantified by comparison of the experimental profiles with computer-generated diffraction patterns of various compositions (Reynolds and Hower 1970).

Organic Carbon

One hundred twenty three soil samples and 29 rock samples were analyzed for organic carbon.

A split of approximately 20-30 grams of sample was taken and, for soil samples, sieved through an 0.84 mm sieve to remove twigs, leaves, etc. The split was ground for 5-10 minutes in a Spex mill, after which approximately 10 grams was removed for analysis. The purpose of grinding more material than was needed

was to minimize sampling errors.

The carbon analyzer used measures only total carbon, so additional treatment was necessary for the organic carbon analyses. The powdered material was dried overnight at 110°C and then cooled to room temperature in a desiccator. Approximately 0.2 grams was then accurately weighed into a glass beaker. The sample was then acidified overnight with 2N HCl. The slurry was washed onto a glass-fiber filter, which previously had been burned off in a muffle furnace at 500°C for one hour to remove organic matter. Approximately 50 ml of distilled water was rinsed through the filter to remove traces of the HCl. The filter was stored in a clean petri-dish until analysis time.

Each filter paper with soil or rock material was folded into a small package, then placed into a disposable crucible. This was dried at 100°C to remove moisture. The crucible with material inside was then analyzed.

All analyses were performed on a LECO WR12 Carbon Analyzer. The Analyzer works by combusting the material inside the crucible to 1600°C. Any carbon present in the solid is volatilized to CO or CO_2. The CO is oxidized to CO_2, other gases are scrubbed out, and the CO_2 is measured by thermal conductivity.

The Analyzer was calibrated by use of standards whose carbon contents are well-known. Two or three standards were run before and after every group of ten samples. The carbon values of the standards bracketed those of the samples. Blank filters were also analyzed after every group of ten samples analyzed for organic carbon. Also, two replicate samples were run in each group of

ten samples. Replicate samples were prepared by taking two portions of the powdered splits, and then preparing and analyzing each. This then gives an indication of the precision of the weighing, acidification, filtering, washing, and analyzing steps, but not of the initial splitting and powdering steps. The amount of carbon measured by the Analyzer is converted to actual weight per cent carbon by dividing by the known dry weight of the sample used.

The calibration of the Analyzer was adjusted to the given tolerance of the standards (± .005% to ± .011%). Replicate analyses enabled the determination of precision estimates. Overall, values for organic carbon are most likely accurate and precise to ± .03% (absolute), or ± 3% relative error. (The mean spread of all replicate analyses run is only .01% [absolute]).

Soil Texture

Soil textures were determined by the Bouyoucos (hydrometer) method, using 50 g air-dried soil (Bouyoucos 1936, 1953, 1962).

Extraction of Water Soluble Soil Salts, pH

Thirty grams of air-dried soil were placed in 250 ml polyethylene sample bottles along with 150 ml distilled water and shaken continuously for five minutes in an automatic sample shaker. The pH of the slurry was measured by a buffer-standardized pH-meter using glass-calomel electrodes. The sample was put back into the shaker for 48 hours.

After 48 hours, the bottles were centrifuged to remove solids and the supernatant liquid was extracted and again measured for pH.

Readings after 5 minutes and 48 hours were so similar that the 5 minute reading was discontinued for the majority of the samples.

Electrical Conductivity

Dissolved solids in supernatant solutions extracted for salts were estimated by means of specific conductance. Measurements were made with a Barnstead Model PM-70CB laboratory bridge and platinum electrodes. The apparatus was calibrated with 7.02 x 10^{-3} N KCl (specific conductance at 25°C = 1.000 mmho). Temperature was measured at the time of the conductivity reading and the observed value was corrected to 25°C assuming that conductance changes 2% per degree. Over-all errors in the procedure amount to about ± 1%.

Soluble Sodium

Sodium was determined on the extracts by analysis on a Perkin-Elmer 503 atomic absorption spectrometer. For most analyses, the primary sodium absorption wavelength (589 nm) was used, and the burner head rotated as necessary to keep sample absorbance in the range of 0.0 to 0.2 absorbance units. The ten or so samples highest in sodium were analyzed using the secondary wavelength (330 nm), again adjusting the burner head as required. In all, four different combinations of wavelength and burner head orientation were used. Because of this flexibility, samples were not diluted; all were analyzed without any pretreatment.

The absorbances were quantified by use of standard calibration curves. For each set of conditions, a stock 1000 ppm Na solution was diluted in distilled water to make four or five

standards. The absorbances of these standards were measured, checked for linearity, and then used as the calibration curve for the operating conditions. The unknowns were quantified by use of the calibration curves.

A basic problem with this sort of quantification is the lack of a similar matrix in the standards compared to the unknowns. Unknown enhancement or depressive effects in the unknowns may affect the sodium absorbance, and the effects would not be seen in the standards. Three samples were analyzed in the usual way, and then analyzed by the method of standard additions. In each case, the sodium value as calculated by the method of standard additions was 1.22X to 1.27X higher than the value calculated by the standard calibration curve. It appears that a matrix component present only in the real samples is depressing the sodium absorbances. If this is true of all the samples, all the reported values should be multiplied by a factor of about 1.2. The reported values are those obtained by the standard calibration curve only. No correction factor was applied.

Several replicate analyses, run using different operating conditions as described above, indicate that analytical precision is roughly ± 2-3%. For very high concentrations (>500 ppm), precision is ± 10%. Sodium concentrations greater than 1000 ppm are less reliable, as the highest standard was only 1000 ppm. Accuracy is probably only ± 20% because of the unknown matrix effects described above.

Soluble Sulfate

Sulfate determinations were made on extracts by means of the

barium sulfate turbidometric method (Standard Methods 1971). Absorbances were measured with a Bausch and Lomb Minispectronic 20 utilizing a two-cm sample pathlength. Samples were diluted with distilled-deionized water to bring concentrations down to the linear region of the absorbance-concentration curve. Replicate determinations indicate a precision of about ± 10% absolute.

Calculations of Theoretical Specific Conductance and Gypsum Saturation Index

Values for ppm Na and ppm SO_4 were converted to microequivalents per liter of Na and SO_4. The sample was assumed to consist of a mixture of Na_2SO_4 and $CaSO_4$ (gypsum) in solution. Thus $[Ca] = [SO_4]-[Na]$. The values for [Ca], [Na], and $[SO_4]$ were computer-processed to provide calculated quantities for specific conductance and the gypsum saturation index, G.S.I., where

$$G.S.I. = \frac{[Ca][SO_4]}{K_{sp}\ (Gyps)}$$ (K_{sp} = solubility product of gypsum)

Solutions for which the G.S.I. >1 are oversaturated, G.S.I. = 1 defines saturation, and G.S.I. <1 denotes undersaturation in gypsum. The computer program used takes into account activity coefficients and ion complex formation. The algorithm is described by Reynolds (1978).

Field Description of Shale Sites and Vegetation

On the several field trips to collect Mancos shale samples throughout the Colorado Plateau and adjacent areas, observational notes were made of the relation of apparent characteristics of

the Mancos shale to the species distinctive of each site. Variations of vegetational composition or coverage which occurred in different topographic situations were noted, as well as the contrasting vegetation growing on sandstone strata or sandstone-derived soils in a nearby area. Because of the extensiveness of the Mancos deposits the area of sampling also included a variety of climatic regimes with resulting typical vegetational types. These varied from ponderosa pine (*Pinus ponderosa*) to saltgrass (*Distichlis* sp.) on encrusted salt flats in areas of less than 4 inches annual precipitation. On the preliminary field trips, in addition to shale samples, some samples of shale-derived soils were obtained from under adjacent vegetational types to ascertain any obvious causative factors for species selection. Also, samples of weathered versus underlying unweathered shale were obtained.

Transects of Vegetation and Soils

On the basis of the preliminary observations and correlations of vegetational surveys with preliminary observations of the lithology of the Mancos shale throughout the region, we selected five principal sites at which to conduct more detailed analyses of soils, underlying shale, and the zonation and composition of vegetation occurring along transects across the zones. Each of the five sites was selected to illustrate a somewhat different situation. Near Mancos, Colorado (the type locality of Mancos shale) a relatively steep hillside was selected which exposed a variety of Mancos strata having different physical, chemical, and resulting vegetational characteristics. In addition, there was a

slope below of relatively deep alluvium composed of weathered shale. South of Thompson, Utah, an area was selected to illustrate the influence downslope of a thin sandstone cap on a hilltop. East of Thompson a site was selected to illustrate a profile of residual soil formed <u>in situ</u> from the weathering of underlying shale. East of Austin, Colorado, a long extensive gentle slope illustrated a zonation of arid shrubs on a thin mantle of variable shale and terminated in apparently saline silty-clay supporting greasewood. The site north of Loma, Colorado, represented a gentle slope with clearly defined zonation of several shrub species typical of the Great Basin. Finally, a sequence was obtained from an extreme condition midway between Page, Arizona, and Kanab, Utah, along the east side of the Paria River. This site was on the saline, highly montmorillonitic Tropic shale. Here there was a strong influence of deep bentonite layers just above the oyster beds of the top of the Cretaceous Dakota sandstone.

At each site the vegetation was delineated into zones. Total foliar cover and relative coverage by species were determined. The distance of each vegetational type along the transect was recorded and measurements made of the slope. Soil pits were dug at appropriate places along the transect to represent the vegetational zone and the transitions from one type to another. From the side of the pits, soil samples were obtained from the near-surface and subsurface depths. These were preserved in plastic twirl bags for laboratory analyses.

RESULTS AND DISCUSSION

Field Observations of Shale-Vegetation Relationships

Although the Mancos shale was laid down in an inland sea, there were many fluctuations in water levels and depositional conditions. Generally the upper Mancos is capped by the blocky sandstones of the Mesa Verde group and is underlain by the Dakota sandstone. However, in between are great variations both vertically and laterally. Often the upper Mancos is interbedded with layers of varying thickness of sandstone similar to the overlying Mesa Verde. The upper layers of Mancos are also usually very sandy. These structural aspects result in the continuation of cliff faces down into the upper Mancos. All of these features are well illustrated in Fig. 2. The effect on the landform of the change to a more uniform silt-clay shale is shown in Fig. 3 where the latter results in highly eroded, dissected, barren slopes.

Interbedded layers of sandstone, which may occur anywhere within the depth of hundreds of feet of Mancos, especially on the western side of the basin, such as shown in Fig. 4, have several effects on topography and vegetation. Erosion may occur down to such a layer which then serves as a caprock forming a plateau and holding up the underlying, softer shale. Disintegration of the sandstone adds coarse blocks, plates, chips, and sand to the weathered shale slopes below, producing important changes in texture, water relations, and vegetational growth. Other effects of the sandstone layers relate to fracture patterns.

Fracture lines in the sandstone are often continued in the shale layers below and become apparent as yellow bands several inches wide of weathered shale on either side of the fracture. These weathered planes may form a network vertically, diagonally, and horizontally. That the process of weathering creates some change which removes from the unweathered dark grey shale an inhibitive factor for plant growth is indicated by the selective growth of evening primrose (Oenothera sp.) on the weathered band, Fig. 5.

The erosion of an interbedded sandstone layer, such as the deltaic Ferron sandstone west of Green River, Utah, leaves a mantle of silty sandstone fragments across the surface of the lower Mancos shale, Fig. 6. The mantle has the appearance of a desert pavement, protects the underlying shale from erosion and serves to improve moisture relations by "water harvesting", in addition to improving the soil texture.

The lower Mancos beds are underlain by the widespread Dakota sandstone, represented by the light colored bedrock in Fig. 7. The stand of pinyon-juniper (Pinus edulis - Juniperus spp.) in the above illustration is dependent on the soil porosity provided by the layer of sandstone. Frequently the shallow margins of the inland sea after the deposition of Dakota sandstone provided favorable conditions for the development of extensive beds of ammonoids and various molluscs. These oyster beds provide a distinct boundary at the base of the Mancos shale.

The shales themselves provide a great variety of physical and chemical characteristics. At one extreme are areas of very

solid, blocky, fine-textured grey shale, Fig. 8. At the other extreme, Fig. 9, the shale may have a very thin, platy structure. Distinct chemical differences may include high concentrations of iron oxides as shown above, high concentrations of deposits of white crystals of gypsum, or coatings of masses of yellow deposits of various forms of sulphur. Values for pH may be as low as 3.4. Conversely, calcium carbonate concentrations may be very high and pH values may be as alkaline as 9.4. In some areas the stratigraphically lower shales may have layers of poorly consolidated black, sedimentary mud looking like organic-rich lacustrine deposits. With the above variations in physical and chemical properties, variations in vegetational response within any one climatic regime would be expected and, of course, different vegetational communities between different climatic regimes on the same type of shale would occur.

Within the climatic variations of the Colorado Plateau Province, from which the Mancos shale samples were obtained, the presence of a sandstone layer is the most striking feature influencing the vegetational response. Whatever the climatic regime, the most mesic vegetation of the area is on the exposed strata of fractured sandstone. In the more moist areas of the northeastern part of the Province such areas are occupied by ponderosa pine, Fig. 10. On the eroded rubble and talus slopes with a mixture of sandstone and Mancos shale are stands of pinyon-juniper, oak brush (*Quercus* spp.), and mountain-mahogany (*Cercocarpus* sp.). Lower slopes and valley floors composed of transported and well-weathered shale-derived soils are dominated

by native, high-producing grasslands. If the moisture supply is great enough to provide for sufficient weathering, knolls with only a small amount of weathered sandstone added to the shale support stands of deep-rooted ponderosa pine with a typical pine forest understory, Fig. 11. Some exposed slopes in the same area are occupied by pinyon-juniper, and steep slopes of shale with no weathered sandstone are barren. In less moist areas the ridge tops, if capped with a layer, or fragments, of sandstone are local sites of pinyon and Utah juniper (*Juniperus utahensis*), Fig. 12. Scattered trees also occur in erosional areas where sandstone fragments from above have accumulated in the drainage. These sites also contain shale which has been subjected to the most weathering and leaching. These processes would result in the amelioration of the inhibitive influence of high salt concentrations or unfavorable pH status. Lower slopes here are dominated by bunchgrasses, indicative of favorable moisture, good infiltration, and deep rooting. In more arid areas, e.g., Meeker, Colo., Fig. 13, the proximity to the upper Mancos with its sandy-silt texture, plus remnants of the weathered overlying Mesa Verde sandstone result in a relatively rich vegetation dominated by big sagebrush, plus some other shrubs such as juneberry (*Amelanchier* sp.), rabbitbrush (*Chrysothamnus* sp.), Forestiera (*Forestiera neomexicana*), and mahonia (*Berberis repens*). Indicative of the sand component of the soil are the presence of Indian ricegrass (*Oryzopsis hymenoides*) and puccoon (*Lithospermum* spp.). Outwash areas from steep barren slopes of shale have a less luxuriant vegetation which is lower in height and coverage.

Valley areas, however, support a good cover of grasses and streamside riparian woody vegetation of cottonwoods (Populus spp.). Again, these alluvial soils have been more completely leached and weathered.

In a more arid region of 4 to 5 inches annual precipitation, e.g., in southeastern Utah, the vegetation is represented by species of the arid, saline, Great Basin flora. In Fig. 14 is shown an extensive, gently sloping plain which for miles is covered by a mantle of flaky sandstone rubble, resembling a desert pavement. The soils are about 6 to 8 inches thick over shale bedrock and are weathered brown and clayey-silt but with some coarse sand. The total shrub cover is about 20% with the dominant being shadscale. There are a few plants of horsebrush and some snakeweed (Gutierrezia microcephala). Occasionally there are some plants of Indian ricegrass, again indicative of the sandy character of the soil. It is suggested from the repeated occurrence of shadscale on similar sites that its presence here is due to large extent to the addition of the mantle of platy sandstone which provides for water conservation, evaporation reduction, and temperature amelioration. On lower slopes the soils are greyer, higher in silt and clay, and not mantled with sandstone fragments. Here the vegetation is very sparse, dwarfed, and exhibits changes in species composition to even more drought-resistant desert shrubs.

The next step in the relationship of shale-associated sandstone and climate is the more arid situation illustrated in Fig. 15. The tops of the hills are mantled with a cobbling of

sandstone fragments as illustrated by the coarse, brownish mantle on the hill to the left. In the area of the 6 to 8 inch deep sandy-silt soil the shrub cover of 20% is dominated by snakeweed and shadscale. The herb cover has sand indicators such as Indian ricegrass and Russian thistle (*Salsola kali*). Down the slope the soils become less sandy and are composed of several inches of silt over weathered shale. Shadscale and snakeweed are replaced by mat saltbush and buckwheat (*Eriogonum* spp.). Farther downslope as the soils become lighter grey in color and with less slope, there is an increase in horsebrush. The color change of soil and reduced height of vegetation can be seen on the lower slopes of Fig. 15. This growth response occurs even though the soils are of finer texture (thus, higher water-holding capacity) and receive some runoff from the upper slopes. This point is emphasized because coarse, sandy soils are so frequently referred to as "droughty soils".

Another illustration of the influence of a mantle of non-shale is that of Fig. 16 where a deep, 8-foot layer of outwash of gravel, cobbles, and boulders overlies an eroded surface of Mancos shale. Because of the porosity of the mantle there has been extreme weathering of the underlying shale which has become tannish-brown in color with staining of iron oxides and has an abundance of gypsum. The coarse mantle provides for a dense vegetative cover of pinyon-juniper with oak brush of Gambel oak (*Quercus gambelii*) - a vegetation not found on the unmantled shale of this area.

In contrast to the previous capping materials which were

more coarse in texture is the common situation illustrated in Fig. 17. Throughout the Colorado Plateau the Mancos shale is interbedded with strata of whitish-colored bentonite. This is a clay, principally montmorillonite, formed from the decomposition of volcanic ash. On exposure, the color changes to light cream, then to yellow, and sometimes to brownish-red. Because of the high montmorillonite concentration, the layer has great ability to adsorb and absorb water and to swell. This causes a sealing of the surface when wet preventing water infiltration and thus providing a protective cap for underlying strata even though when dry it is relatively unconsolidated. In areas of low rainfall it is able to absorb all of the available moisture and thus its chemical constituents often do not leach into adjacent strata. The yellowish color illustrated is common on many of the rounded plateaus and knolls throughout the arid region of the Colorado Plateau. In color it is not distinct from the yellowish tan produced by a mantle of fragments of sandstone but its effects on vegetation are quite different, favoring arid zone, shallow-rooted, salt-tolerant species such as mat saltbush and horsebrush.

An extreme example of the combined effect of a thick bentonite layer on the surface and a very saline shale is that of the Tropic shale as illustrated in Fig. 18 from the area between the headwaters of Wahweap Creek and the Paria River in southern Utah. Here the combination of high sodium concentration, high percentage of montmorillonite, and an annual precipitation of less than 4 inches results in an unusually barren landscape. The complete absence of vegetation caused by a thick surface cap

of bentonite is illustrated in the triangular area in the center of Fig. 19. A sparsely vegetated area of Tropic shale, not capped by bentonite, and the site of transects referred to later is shown on the left. The white powdery bentonite layer 8 to 12 inches deep and weathered on the surface to a tannish color is shown in Fig. 20. In an exceptional year, with late winter snows, the shale flats may produce an amazing, but temporal, display of spring growth as illustrated in Fig. 21. Dormant corms of mariposa or sego lily (Calochortus sp.) suddenly send up flowering stalks. Species of buckwheat, such as desert trumpet (Eriogonum inflatum) typical of gypsum soils, produce masses of yellow flowers and green inflated stems. Species of Erigeron and Phacelia quickly come into flower. Even the slow-growing, grey mat saltbush for a short time looks almost lush and green.

Another relationship of shale soils to vegetation which has been observed in the field occurs along transects of gentle slopes. Vegetational zones often occur at contour intervals along a slope. Although there is evidence of some surface runoff down the slope which would mean that the lower slopes received more surface water than the upper slopes, the vegetation does not become progressively taller or more vigorous downslope. To the contrary, the tallest vegetation is frequently at the top of the slope. The exception is greasewood (Sarcobatus vermiculatus) which occurs on the outwash flats where runoff water may at times be standing on the surface. It is generally stated and accepted that as one proceeds down a slope the soil texture becomes finer and is a principal cause of changes in vegetation. In relation

to the growth of ponderosa pine, which is localized on the tops of knolls on either Dakota sandstone, or in some areas on baked shales as in western North Dakota, it has been previously emphasized that the soil texture is very similar under ponderosa pine and the shortgrass vegetation at the base of the slope (Potter and Green 1964 and Potter 1969). The portion of the soils which is analyzed in the laboratory consists only of particles less than 2 mm diameter. The difference may not be in the textural and chemical analyses but instead in the proportion of the weathered soil, e.g. clay, to the total volume of the natural soil. Where a large percentage of the volume is composed of fractured rock, the surface can not become sealed to prevent infiltration, the fractures allow for moisture concentration and penetration, and the fractures allow for deep penetration of roots. Conversely, a soil volume of 100% clay easily becomes sealed at the surface, prevents infiltration, prevents aeration, and causes shallow root development. The contrasting *in situ* situations under a given climate may result in ponderosa pine under the former and a stand of shortgrasses under the latter.

The depth of weathering forming clay and silt from the underlying bedrock is usually less on the top of the knoll and upper slopes than it is downslope. Also, because of sheet erosion downslope there is a degradation of the upper, and aggradation of the lower slopes with a maximum accumulation at the valley floor or playa. The texture of the weathered material derived from shale may be very similar throughout the slope. But, the depth and resulting conditions for moisture penetration, aeration,

and rooting may be quite different because of the difference in volume ratios of weathered to unweathered mass.

An illustration of a transect across a gentle slope showing a common sequence of vegetational zones and the accompanying soil profiles is presented here and will be discussed further in relation to laboratory analyses. The transect is located 12 miles north of Loma, Colorado. The site of Fig. 22 is located 4.5 miles farther north where the vegetation includes the lower edge of pinyon-juniper and there is a mantle of sandstone fragments over the Mancos shale. This is the nearest such effect. The transect starts at the top of a slope with a dominance of blackbrush (<u>Coleogyne ramosissima</u>) and galleta, Fig. 23. In Fig. 24 is illustrated the brownish weathered soil at this site. Slightly downslope the vegetation changes to a 98% dominance of shadscale with some galleta, Fig. 25. The soil profile is shown in Fig. 26. Midway down the slope is a zone dominated by a mixture of shadscale and horsebrush with some galleta, Fig. 27, on a light-grey deepening soil with a caliche layer, Fig. 28. This area is just above the contour where shadscale is replaced by mat saltbush. Figs. 29 and 30 are near the center of the zone with shared dominance of mat saltbush and horsebrush. Here there is an increase in buckwheat. Below is a zone sparsely populated with mat saltbush as 95% of the cover, Fig. 31. In the soil profile (Fig. 32) is a surface layer of loose friable silt, a narrow band of caliche, and below some evidence of leaching and deposition of iron oxides. The lowest vegetated zone consists of greasewood, Fig. 33, and a typical structureless soil profile as shown in Fig. 34. There is a general increase in surface encrustation

downslope. In some areas within and below the greasewood zone there may be salt flats barren of vegetation and surrounded by stands of burroweed (Suaeda sp.) and saltgrass, Fig. 35. Throughout the above transect there is a slight trend for the depth from the surface to a caliche layer to be less and for the thickness of the caliche to be less the farther downslope the profile is located. Not readily apparent are possible differences in chemical features, such as sodium concentration, which can only be inferred to increase downslope. Its increase would cause surface soils to become deflocculated, fluffy, and to seal off when wetted - thus inhibiting moisture infiltration.

As discussed earlier, most of the relatively level areas of Mancos shale are capped by some other material, e.g., sandstone or bentonite. Broad valleys are usually formed by Mancos alluvium deposited from erosion of relatively barren surrounding hills. In some relatively level areas a soil derived from weathered Mancos is formed in place without a protective cap. Such a residual soil is shown in Fig. 36 in the arid region of southeastern Utah. The upper 5 to 6 inches have a well-developed crumb structure with an apparent favorable calcium:sodium ratio. Underlying strata have good root development in the more platy, less weathered shale. Bedrock is about 15 inches from the surface. With little slope and low rainfall there is minimal opportunity to leach out any restrictive elements, such as sodium, in the residual soil. Thus, the limiting factors of drought, high salinity, and the poor infiltration and aeration of a silty-clay texture restrict the vegetation to drought- and saline-resistant species.

Quite in contrast to the residual shale soils is the situation of weathered, leached, and transported alluvial soils as illustrated by a cut-bank in a broad valley, Fig. 37. These soils in the process of long-distance transport have lost much of their inhibitive sodium content but are still calcareous. A well-structured silty-clay soil develops which allows for deep penetration of moisture and roots. These conditions result in the growth of a healthy stand of big sagebrush with good coverage, vigor, and height over 3 feet. These criteria indicate a situation in which marginal dryland farming is possible. In broad valleys, alfalfa, corn, or irrigated pastures may be successful. Or, native stands of grass provide excellent pasturage, Fig. 38.

Sequences of vegetational zones do not always correspond to physiographic slope or a continuing change in soil profile. Within Fig. 39 there are several apparent correlations of environmental factors and vegetative communities. A cap of sandstone at the top of the ridge has resulted in a fringe of pinyons and junipers. Zones on the slope dominated by buckwheat are interrupted by a barren zone of unweathered highly sulfurous shale. Bands of siltstone and sandstone result in a lower zone of pinyon-juniper. Below is a zone of deep, weathered, alluvial silt which supports big sagebrush in the foreground. Below it is an area of greasewood.

In regions where moisture is a critical and limiting factor, differences in slope exposure also produce an exaggerated effect. In a south-central Colorado outcrop of Mancos shale illustrated in Fig. 40, the relatively barren slope which is southwest-facing

has a sparse cover of shadscale and mat saltbush. A similar angle of slope of the same soil but northwest-facing has a much denser cover of big sagebrush. In the foreground, on outwash material, is a stand of greasewood.

General Results and Implications of Laboratory Analysis

The X-ray studies of clays from shale samples show that the typical mineralogy consists of small amounts of kaolinite and illite, and larger amounts of interstratified illite-smectite, the smectite composed principally of montmorillonite. Except for a few localities near igneous intrusions, the interstratified species is approximately 50% illite - 50% smectite. The range observed is 60I-40S to 40I-60S, with the majority of samples near 50-50.

The X-ray studies of soils and associated shales show no alterations of the clay mineralogy by pedological processes, thus the typical soil developed on Mancos shale contains somewhat less than 50% smectite if allowance is made for the small amounts of kaolinite and discrete illite present. The abundance of sodium in soil solution, the absence of chloride, and the abundance of effluorescent sodium sulfate on outcrops suggests that the soil smectite is sodium-saturated.

The trace elements zinc and nickel, and the organic carbon content of the Mancos have been studied and reported (vanOss 1978). The work was carried out with Dartmouth funds and the samples were selected from the locations shown by Fig. 1. The mean Ni and Zn contents are, respectively, 41 and 92 ppm, and the mean organic carbon content is 1.1%. The Ni and Zn contents are similar to

those reported for average black shales (Vine and Tourtelot 1970), but the organic carbon content of the Mancos is distinctly less, despite the dark appearance of many samples of fresh shale.

Data on soil solutions are given in Figs. 41-47. Depths of samples are given in inches. Texture is expressed as the percentage of sand/clay, the difference between the sum and 100 being the percentage of silt. Values for pH, conductivity in mmhos at 25°C, and percentage carbon are given as discussed in the methods section. Sulfate values are in parts per million (ppm) of the water extract from a soil:water mixture at a ratio of 1:5. The calculated gypsum saturation index (G.S.I.) is given with starred values indicating that the ionic strength of the sample is beyond the limits of the Dehye-Hückel theory; the values for G.S.I. are then inaccurate. Note that most of the solutions that are greatly oversaturated in gypsum (G.S.I.>1) are starred. It is likely that these solutions are at saturation, and that the high values for G.S.I. result from a break-down of the theory at high ionic strengths. Sodium values have been converted to a concentration which would occur in the water of a field saturated soil and expressed as ppm of that solution.

Trace metal, organic carbon, and clay mineral studies of Mancos shale and soils disclose no unusual characteristics that could account for the paucity of vegetation in the study areas. In short, it is a typical marine shale.

Data on pH of soil extracts are quite variable, but most values are in the range of 8 to 9+. These high pH values indicate the presence of significant carbonate alkalinity. It must be

emphasized, however, that the conditions used in the laboratory do not simulate the likely field conditions. Our samples were shaken in sealed containers, whereas in the field, soil solutions doubtless absorb CO_2 from root respiration and the oxidative metabolism of the soil microflora. Thus field pH values should be lower than the extreme high values shown.

Very low pH values were obtained for some soil samples, e.g., from Mancos, Colorado. These acid conditions are most likely due to the presence of sulfuric acid that was produced by the oxidation of pyrite and/or organic sulfide in the shale. Indeed, the abundance of sulfate in soil solutions and the ubiquitous presence of gypsum in Mancos soils and shales attests to the abundance of sulfide in the shale.

Some soil samples contain very high concentrations of leachable sodium. The distribution of sodium in soil profiles shows that it is usually concentrated in the subsoil. Presumably, sodium sulfate is leached downward by percolating waters and crystallizes near the soil-bedrock interface. Sulfate tends to show the same relation but to a lesser extent. Sulfate is more uniformly distributed throughout the profile because of the presence of the more insoluble phase, gypsum. In extreme cases, gypsum has apparently been leached away, as for example in the samples from Loma, Colorado.

Calculated and measured values for specific conductance agree quite well despite the somewhat crude data for sulfate. In general, measured values are greater than calculated ones. The difference reflects the fact that the water analyses contain

no consideration of bicarbonate and its associated cations. The calculated values are based on the assumption that the waters consist only of sodium sulfate and calcium sulfate. The agreement shows that approximately 80% of the major element composition of the waters is accounted for by this assumption.

Calculated values for the gypsum saturation index (G.S.I.) are, for most samples, so close to unity that we conclude that equilibrium with gypsum is an important control on the salinity of the soil waters. Values much in excess of unity are doubtless in error because of the failure of the chemical theory for these solutions, for all are of very high salinity. Values much less than unity are ambiguous because of the conditions used in the extraction procedures. This point is important because it leads to the conclusion that under field conditions, sodium sulfate is much more concentrated with respect to calcium sulfate than the data indicate. The conclusion follows from a consideration of the solubilities of sodium sulfate and gypsum.

The laboratory extractions were performed with 150 ml water and 30 g of soil. Consequently, all of the gypsum could dissolve from soils that contained little gypsum. If twice the volume of water had been used, for example, the gypsum saturation indices for these materials would have been even lower. But in the field, the likely porosity of the soil is near 50% by volume. Thus the solid-liquid ratio by weight is near 2.7 to 1, as opposed to the laboratory ratio of 30/150 = 0.2. The difference between the laboratory and field conditions is thus 2.7/0.2 = 13.5, that is, we used 13.5 times the liquid to solid ratio that one would expect for a water-saturated natural soil. The experimental

approach was necessary because of the difficulty or impossibility of dealing with thick slurries in our analytical procedures. It is likely that almost all soils would have shown G.S.I. values near unity if much less water had been used. In fact, a value of about 1500 ppm SO_4 due to gypsum is the likely one for natural soil waters in all of our samples except, possibly, some of the Loma series. Although recognizing the above potential field situation and reasonable conversion of values, the data for sulfates are expressed as ppm of the water extract at a soil-water ratio of 30/150.

The considerations outlined above do not apply to sodium sulfate. The solubility of sodium sulfate is 47.6 g/l (Handbook Chemistry & Physics 1953). Thus saturated Na_2SO_4 contains 32,370 ppm SO_4 and 15,420 ppm Na, values well in excess of any obtained in the water extract from the soil/water ratio of 30/150. Consequently, the sodium concentrations in our water represent all of the sodium sulfate in the soil. If less water had been used, higher sodium concentrations would have been found. A maximum realistic natural soil value at soil saturation is, as shown above, 13.5 times the concentration in the leachates. This is the converted value for sodium which has been reported in this study. Using the example of a water extract from a soil/water ratio of 30/150 and containing 9.3 ppm of sodium, the water in the soil at field moisture saturation would contain $9.3 \times 13.5 = 126$ ppm Na. Sulfate due to gypsum would be essentially unchanged because the gypsum is at saturation. Such sodium concentrations are too low to pose serious salinity problems to plants, but if the factor of 13.5 is applied to the

data of shales from an arid region, such as the Tropic shale near Page, Arizona, the results show that the soil solutions there are likely to be saturated with respect to sodium sulfate after a rainfall, and contain at soil water saturation maximum sodium concentrations as high as 18,765 ppm! This conclusion is strengthened by our observation of pure sodium sulfate layers in the soil at that location.

The information obtained in the laboratory and in the field can be rationalized into a scheme for the development of water salinity in soils derived from Mancos shale. The first step is the oxidation of pyrite by exposure to the atmosphere. The large amount of sulfur as sulfate in soil solutions argues against the importance of organic sulfur; the ratio of sulfur to organic carbon is too high in the soils. Finely disseminated pyrite is probably the source of the sulfate. Oxidation produces sulfuric acid which, at Mancos, manifests itself by low soil pH values because the lowest stratigraphic unit of the Mancos that is exposed there is deficient in limestone. Other units in the Mancos contain moderate to large concentrations of limestone. For these, sulfuric acid acts on the calcium carbonate to produce the more soluble calcium salt, gypsum. Gypsum is much in evidence in the Mancos, and its occurrence along joints, bedding planes, and fissures shows that it is a secondary mineral. Dissolution of gypsum during wet periods allows ion exchange equilibrium with sodium-saturated smectite (montmorillonite) in the soil. Calcium exchange on the soil improves the soil's physical properties, but accumulation of sodium sulfate in the soil pores can lead to

a condition of very high salinity because of the great solubility of sodium sulfate. Drainage of soil water removes some of the sodium sulfate, but its concentration in the subsoil in several localities indicates that for these regions, rainfall has been insufficient to drive the exchange reactions to completion and flush away the derived sodium sulfate.

Specific Field Transects and Laboratory Analyses

The following transects were selected to illustrate the correlation of vegetation to the laboratory analyses of soils and shales. The first study area is shown in Fig. 39. A summary of the principal features of the area is presented in Fig. 41. Across the top of the ridge is a surface mantled with pebbles of sandstone remnants. Below about 1 inch of fine weathered shale is a soft, black, platy shale into which root systems are found to a depth of 8 inches. The vegetative cover consists principally of species of buckwheat. Although galleta is the principal grass there are depauperate clumps of Indian ricegrass, blue grama grass, and hairy grama (*Bouteloua hirsuta*) in response to the presence of some sand from the eroded sandstone cap. Some parts of the ridge with sandstone have a woody cover of Utah juniper, pinyon, mountain-mahogany (*Cercocarpus montanus*), and juneberry. Sample A is within the *Eriogonum* zone; sample B is at the sharp transition to a barren area. Both samples have a relatively neutral pH and low surface concentrations of sodium. In the middle of the barren area, however, sample C becomes very acidic with subsurface readings as low as pH 3.4. There, and

throughout the area barren of vegetation, the shales at depths of 3 to 14 inches are coated with yellow layers of sulfurous compounds thought to be principally jarosite, $KFe_3(SO_4)_2(OH)_6$, as shown in Fig. 48. Sodium may be substituted for potassium. On wetting and oxidation ferrous sulfate, $FeSO_4$, and ferric sulfate, $Fe_2(SO_4)_3$, would be formed. The production of sulfuric acid would account for the low pH values. If there is an abundance of calcium carbonate present this would tend to neutralize the acidity. If not, the acidity and the use of oxygen by the oxidation of shale minerals would be inhibitive to plant growth. The reaction of sulfuric acid and calcium carbonate would result in the formation of gypsum, which is relatively common in the barren area. Also common at lower depths and in the weathered transported soils of the lower slopes are mottlings and layers of reddish color due to iron oxides released from the above process.

Sample D represents a very narrow band occupied by Eriogonum and limited to a sandstone-rich ledge. In this zone both the pH values and the sodium concentrations are again very low. Sample E within a second bare area is also acidic, with much gypsum and sulfur, and like the barren zone above has a higher sodium concentration than the area occupied by Eriogonom. Above F, the slopes are 54 to 66% and below are 23 to 26%. With the transition from bare area to pinyon-juniper at F there is a sudden rise in pH from 3.8 to 7.9 in surface soils. While surface soils of the ridge are mildly alkaline (7.4 to 7.8) from the pinyon-juniper downslope the soils are moderately alkaline

(7.9 to 8.4) or highly alkaline (8.5+) according to Soil Survey Staff (1951). However, the sodium values are low. The shales are mud-like, not flaky, and not rich in sulfur or gypsum. At the mid-zone of pinyon-juniper, sample G, the soils are alluvial with some sandstone. The pH values increase, as do the sodium concentrations. Here the tree cover of 30% consists of 75% juniper, 20% pinyon, and 5% Gambel oak. The shrub cover of 20% consists of 80% big sagebrush, 15% mountain-mahogany, 4% juneberry, and 1% rubber rabbitbrush (Chrysothamnus nauseosus). The sparse herb cover consists of thymeleaf spurge (Euphorbia serpyllifolia), bluebunch wheatgrass (Agropyron dasystachyum), buckwheat, evening-primrose, and globe mallow (Sphaeralcea sp.). At the transition between pinyon-juniper and big sagebrush, sample H, there is a further increase in the alkalinity and a sharp increase in sodium concentration in the soil. Both of these increases continue into the sagebrush-greasewood zone. As expected in this zone the percentage of sand decreases as the silt and clay increase. Here sagebrush and greasewood are codominant. The herbaceous vegetation consists principally of alkali sacaton, western wheatgrass, and bottlebrush squirreltail (Sitanion hystrix).

From the Mancos transect it would appear that sodium concentrations may be more restrictive to plant growth when pH values are acidic and that a good growth of vegetation may occur on soils in moist areas when values of sodium increase up to as much as 189 ppm in a field saturated soil solution if the soils are alkaline in the area of pH 8.0. This growth occurs in spite of the reduced solubility of phosphorus, iron, manganese, copper,

and zinc ions under alkaline conditions (Brady 1974).

A second detailed transect was examined south of Thompson, Utah, in an arid region supporting shadscale. Commonly here and elsewhere the knolls are capped with a mantle of fragments of sandstone which provide for erosional protection and for water-harvesting. The northeast slope of the hill which was transected is illustrated in the right side of Fig. 15. Note the change in density of vegetation from the top downward, and the nearly barren south-facing slopes on the left. Note also the change in soil color to a greyish appearance near the bottom. The summary of Fig. 42 indicates that in this lower area the soils are about 85% silt. The vegetation of the knoll is that of snakeweed-shadscale with an herb cover of galleta, Russian thistle, and Indian ricegrass, all of which are favored by relatively light surface soils. Here the sandy soil is 6 to 8 inches deep, calcium carbonate rich, alkaline, and low in sulfate concentration. The underlying shale down this slope appears to be of a siltstone nature. The surface sandstone fragments end at sample B, at which point there is a high concentration of sodium and a decided decrease in total vegetative cover. The fine weathered silty soil is much shallower (2 to 3 inches) in samples B and C. The subsurface sulfate concentrations average 800 ppm in the shadscale zone. The pH values remain at 8 to 9 downslope. Surface soils of the upper slope have sodium concentrations of 27 to 54 ppm which increase in the lower grey soils coincident with the introduction of horsebrush. The change in dominance from shadscale to mat saltbush at sample D seems to be related to the

increase in conductivity and to the doubling of sulfate concentrations in the subsurface layers. The increased cover in the mat saltbush zone is due principally to the low, mat-like growth of this species and the additional cover of horsebrush. At the lowest level sampled there is an increase in sodium concentration and the highest values for conductivity at this site.

Generally this transect represents a dual influence of a sandstone cap and a siltstone type of shale plus the lack of an acidic condition. The more favorable rooting in a porous soil is indicated by the presence of Indian ricegrass. The increase in concentrations of sodium and sulfate and the conductivity downslope is suggested as being responsible for the shift from shadscale to mat saltbush and then to horsebrush. The latter is most common on the greyish, silty soils which begin where the slope changes from about 50% to 15%. Here also, the soil surface is patterned with contraction cracks and the small bumps in the irregular surface are eroded off into rounded domes.

A profile was obtained in an area several miles east of Thompson, Utah, where the shales appear to have weathered in place, Fig. 36. Here there are about 5 to 6 inches of completely weathered, non-laminated shale with a crumb or nut structure. From 6 to 14 inches the soil is of fine, flaky structure with brown and black bands. Below 14 inches is the coarse, platy, dark-grey unweathered shale. Roots are common down to the latter. The dominant plant species is mat saltbush with a few plants of buckwheat. The soil properties are summarized in Fig. 43. The soils are about 85% silt. The pH values are consistently alkaline

at all levels, but most alkaline in the unweathered shale, indicating a lack of sulfides here. The conductivity values are the highest of any Mancos shale samples from all transects. The increased values of sodium from 40 ppm in the surface soils to 2511 and then to 5899 ppm at the 5 to 10 inch depth indicates a leaching downward of salts, even in this area of low rainfall of about 4 inches per year. There is also an accumulation of very high concentrations of sulfates at this level which are exceeded only in the Tropic shale samples. The reduction of sodium in the surface layers and the presumed common presence of calcium has allowed for the development of soil structure.

The transect which illustrates a gently sloping topography with smooth, rounded knolls apparently controlled by bentonite layers is 2.3 miles east of Austin, Colorado, Fig. 17. The transect extends from the knoll in the center downward to the left at about a 9% slope until it reaches the bugseed (Corispermum sp.) and greasewood zones. The analyses are summarized in Fig. 44. Across the top of the knoll a soil profile, Fig. 49, reveals a 1 to 2 inch layer of fine, loam-textured, dark-grey, unstructured soil with a relatively high (378 ppm) concentration of sodium. This is one of the few instances where the sodium is higher at the surface. Below is a foot-thick layer of whitish bentonite, mottled with streaks of yellow. Underlying shales in this area are frequently coated with sulfurous compounds. While the top of the knoll has a 15% shrub cover of horsebrush and mat saltbush, only the former occupies the upper slopes. It is suggested from other data that shadscale does not occur here

because of the high sulfate values. But there is no obvious reason from the analyses why mat saltbush does not occur on the upper slopes where the soils are lower in sodium concentration than across the top. The soils below the lower limits of horsebrush, sample C, are lower in sand percentage and are principally silt within the barren area. At sample D within the barren area the surface has an irregular, knobby contour resulting from expansion and desiccation cracking. There are many crustose lichens. At 2 to 6 inches there is dark brown consolidated silt. Below that the soil becomes progressively black but with mottling of white caliche. Subsurface soils are very high in sodium concentration, the highest for this transect. At sample E, within the narrow zone of bugseed, the soils are alluvial and of a loamy texture. The surface 1 to 2 inches are loose and powdery due to 135 ppm of sodium which apparently does not prevent germination of some seeds. Then at 2 to 6 inches there is a dark brown consolidated zone, below which is a compact calcium carbonate cemented hardpan with a high sodium concentration. Within the greasewood zone, sample F, the pH values increase to 9.2 at the surface and the highest sodium concentrations recorded for surface soils are found here, except for the area of Tropic shale. It is thought this salinity prevents the development of herbaceous ground cover. The surface has a crust, probably due to the salinity; below are 2 inches of loose, friable, fine soil; but below the 2-inch depth there is a hardpan of caliche. The sharp transitions of vegetation of D-E-F are illustrated in Fig. 50 from the barren area across a narrow

band of bugseed to the greasewood zone. Although no surface soils were analyzed for sulfate, the values of subsurface depths were relatively high throughout this transect.

At the same site discussed above, Fig. 17, there is a steeply eroded southern exposure shown on the right of the photo and detailed in Fig. 45. The barren area is the exposure of the shale beds on the steep slope (54%), where in addition to soil instability preventing vegetational growth, the shale here is very acid, high in sulfates, and relatively high in sodium. Weathered material from the steep slope accumulates in the lower slope starting at sample C where 5 inches of fine, black, silty, weathered shale are underlain by a platy shale of pH 5.1. Roots are common within this shale layer. Within the zone of buckwheat shown at the lower right of Fig. 17 and at the site of sample D, the surface pH at 0 to 0.5 inches is 8.0 but at a 2 inch depth is 4.1. Values are high for sulfate and gypsum saturation index, and relatively low for sodium, which would favor the gypsiphilic species of Eriogonum. It was observed at Mancos, Colorado, that buckwheat is able to grow in a band of shale when subsurface layers are pH 3.8 but not on either side of the band where subsurface pH values are 3.4.

The most complete series of vegetational zones down a slope and perhaps most representative of the arid Four Corners area was studied about 12 miles north of Loma, Colorado. About 4 miles farther north is the upper part of the Mancos shale and here there is a mantle of weathered fragments of the overlying Mesa Verde formation, Fig. 22. With no climatic change in the four

miles, this area is able to support the lower edge of pinyon and juniper. In the area of the transect there is a slight effect of weathered remnants of sandstone on the top of knolls. The profile and summary of the transect is given in Fig. 46.

The upper vegetational zone is dominated by blackbrush and the herb cover by galleta and fescue (Festuca sp.), Fig. 23. Here the soil profile, Fig. 24, is dominated by alluvial sand with a loose, friable, sandy-colored zone overlying a foot of more compact, brown, structured, sandy alluvium. Roots are common in the upper 8 inches of the soil. Samples B, C, and D were obtained in an attempt to ascertain a causative factor of the change from blackbrush to shadscale. The only apparent cause is the increase in subsurface concentration of sodium. The values for sulfate are consistently very low. Values for pH vary slightly with vegetational zones throughout the transect. The condition of acidity resulting from sulfur is not a problem here. In a study of indicator shrubs in the Escalante Desert, Fireman and Hayward (1952) found average pH values between plants and under plants to increase as follows: sagebrush 8.46 and 8.41, shadscale 8.66 and 9.23, and greasewood 9.00 and 9.83. They also found that both shadscale and greasewood significantly increased pH, conductivity, and exchangeable-sodium percentage under plants and increases were related to size of plants. In a detailed study of soil factors influencing plant distribution of salt-deserts by Gates, Stoddart, and Cook (1956), no statistically reliable difference was found between pH values of five species studied, including sagebrush, shadscale, and

greasewood. However, salt concentrations, as expressed by conductivity, significantly increased in order under big sagebrush, winterfat (Eurotia lanata), shadscale, greasewood, and Nuttall saltbush (Atriplex nuttallii). Also, under each type the conductivity increased with depth. They found sodium concentrations increased with depth and concluded that the maximum amount of exchangeable sodium a species could tolerate affected its distribution. Sodium tolerance increased as follows: sagebrush, winterfat, shadscale, Nuttall saltbush, and greasewood. Concentrations of soluble sodium reported varied from 719 ppm to 2215 ppm. It is suggested from the data of this current study that blackbrush would be similar to sagebrush in its lack of sodium tolerance.

Not revealed in the data is the observation of differences in the soil profiles at B, C, and D across a distance of 8 meters. All have about 2 inches of loose weathered soil at the top, but the depth to a hard, compact, caliche layer decreases from about 6 inches to 2.5 inches going downslope. Blackbrush is known to be more common on sandy soils than in situations with a caliche layer near the surface.

The stand of shadscale with its understory of galleta is illustrated in Fig. 25. The soil profile within this zone, sample E, is shown in Fig. 26. The appearance and analysis of the profile are similar to those of the upper and lower edges of the zone. The addition of horsebrush occurs near the lower part of the shadscale zone and the dominance becomes shared between the two shrubs as shown in Fig. 27 where the horsebrush

is distinguished as being the taller and lighter grey in color. The soil profile, Fig. 28, within this zone appears similar with 2.5 inches of loose silty-clay overlying a relatively thin lime-cemented soil to a depth of about 6 inches, below which is a weathered flaky shale coated with lime. Roots extend down to 12 inches in depth. Apparently the caliche layer is not impervious.

At sample G there is a transition of the species of Atriplex from A. confertifolia to A. corrugata. Sample F is 4 meters above G, and H is 4 meters below the transition. Based on the field observations, the caliche layer becomes somewhat thinner from F to H. The laboratory analyses show a dramatic increase from very low sulfate values from site A to F. Then at G, where the change is from shadscale to mat saltbush, water extracts from the subsurface soils increase in concentration from 30 to 1650 ppm within 4 meters distance. This is one of the best correlations of chemical change and resulting change in plant species, which here changes from 14% coverage of shadscale to 14% coverage of mat saltbush. The only other distinguishable changes in the laboratory analyses are the increases in conductivity - which persist downslope, and the slight increases in the sodium concentration. Fig. 29 illustrates the vegetation with mat saltbush on the left. A typical soil profile within the zone at sample I is illustrated in Fig. 30. It is somewhat more alkaline and higher in sodium. Here, however, there are only 1 to 2 inches of fine-weathered soil over weathering, flaky shale into which roots have readily penetrated. There is no clearly defined caliche layer. Where the horsebrush

drops out and mat saltbush is nearly sole dominant at sample K, Fig. 31, the surface soil, as elsewhere in this zone, becomes bumpy as though the result of solidification of a frothy surface. This is actually the result of repeated sequences of expansion and contraction. From field observations, the transition soils at J have a caliche layer at the 2 to 4 inch depth with roots abundant to a depth of 9 inches extending into the grey, weathering shale. At K the caliche layer is at a depth of 2 to 3 inches with underlying weathering shale showing deposits of iron oxides and deep root penetration, Fig. 32. The conductivity values and sodium concentrations remain high in these samples. The analyses do not explain the distribution of horsebrush.

Far downslope from the transect is a stand of greasewood which is illustrated in Fig. 33. Of the 30% shrub cover, 95% is greasewood. Other cover consists of burroweed and alkali sacaton. In this zone, soils are light in color, often encrusted and cracked at the surface with several inches of powdery unconsolidated soil overlying many inches of hard, silty-textured soil, Fig. 34. Laboratory analyses of this soil indicate an increase in pH to 9.0, a reduction of sulfate to 170 ppm, but a great increase of sodium to 1687 ppm which would favor greasewood. There is a lack of gypsum here.

A final transect was examined to illustrate one of the most extreme edaphic and climatic conditions. This area of shale is referred to as Tropic shale and the site is between Page, Arizona, and Kanab, Utah, along the east side of the Paria River. As described previously, Figs. 19 and 20, several deep layers of

bentonite are interbedded in the shale and frequently form a cap over the smoothly eroded topography. Most of the knolls and upper slopes are essentially devoid of vegetation. Fig. 47 is a summary of one of the transects in Tropic shale, illustrated on the left side of Fig. 19. The surface 2 inches of soil are dark grey with a crumbly crust at the surface and fine powder below. Outstanding is the surface concentration of sodium based on soil solution of a water-saturated soil of 17,550 ppm! Composed principally of montmorillonite and with this high sodium concentration, these soils when wet would swell and form an impervious gel across the surface. A bentonite layer several inches thick (100% clay) seems to have sifted downward into the fractured shale below which is mottled with iron oxides. On the barren slope at sample B the slightly weathered shale is exposed at the surface and the sodium concentrations of surface and subsurface are about 8000 ppm. Common throughout the rocky subsurface are large clusters of gypsum crystals. At the base of the slope, sample C, about 2 inches of weathered, and probably transported, silty-clay overlies a finely-fractured platy shale. The surface layer here has the lowest sodium concentration of the surface soils within this transect, 1417 ppm, but is underlain by sodium concentrations of 18765 ppm which may account for the absence of vegetation. In addition, sulfate concentrations are very high and the G.S.I. values exceed unity. At station D the soils appear to be outwash accumulation more than a foot deep; however, sodium concentrations of 4036 ppm in surface soils and 8032 ppm in subsurface soils occur and do not prevent the growth

of mat saltbush. At station E a layer of 2 inches of fine, grey dust covers a zone from 2 to 6 inches in depth of large crumb structure, below which is a finer, granular, mottled, brown layer extending down to 18 inches. Root penetration occurs 18 inches and more deep. Remarkably, the widely-spaced, low, matted plants of mat saltbush are growing in these soils of 2524 ppm sodium at the surface and 17685 ppm in the subsurface, indicating an extreme sodium tolerance! Yet, the species does not grow at sample C where the surface soils are lower in sodium concentration. It is concluded that the greater depth of weathered soil at D and E allows for mat saltbush to grow in spite of the high concentrations of sodium. These soils also are very high in sulfate concentration and gypsum saturation.

In addition to the laboratory analyses of soils along the transects, a large number of paired samples were obtained to contrast different vegetational types. Some of the results are reported here. Analyses were done on a pair of samples of shale bedrock taken from the fracture shown in Fig. 5. The question was, why can evening-primrose grow on the light-colored weathered shale next to the fracture and not on the unweathered grey shale. The analyses provide the following results of the weathering: a lowering of pH from 8.4 to 8.1; a doubling of conductivity from 0.5 to 1.1; a slight reduction from 113 to 108 of sodium in ppm of a saturated soil solution; but an increase in sulfate from 160 to 540 ppm of a saturated soil solution and an accompanying increase in the gypsum saturation index from .04 to .27. Whether other structural changes may be important is not known.

A set of paired samples from near Lone Cone, Colorado, was analyzed to contrast the soils supporting a stand of grass dominated by western wheatgrass, bluebunch wheatgrass, and bluegrass (Poa sp.) to an adjacent soil under the litter and growth of ponderosa pine. The site is illustrated in Fig. 11. The similarity of the results of the laboratory analyses is remarkable and provides no clue for the cause of pine versus grass and shows little change in the soil resulting from these vegetative types. The comparison follows: pH 7.3 and 7.3; conductivity 0.2 and 0.2; sulfate <40 and <40; sodium 13 and 16 ppm.

The distribution of galleta grass is often spotty. Analysis of samples from within a patch of this grass indicate a lower concentration of sulfate than in non-grassed areas at the same site. This relationship is also seen in the transect at Loma, Fig. 46. Within the shadscale zone the sulfate values are low, as these values rise sharply in the mat saltbush zone the coverage of galleta declines.

A pair of samples collected near Green River, Utah, was analyzed to determine the differences between the bedrock shale and the overlying weathered soil which has formed in place. The analyses are nearly identical between bedrock and soil: pH 8.2 and 8.3, conductivity 3.3 and 3.7, sulfate 2070 and 2600 ppm, G.S.I. 1.10* and 1.57*, and sodium 4941 and 5265 ppm. As would be expected from the high sulfate and sodium values this area is dominated by low-growing mat saltbush.

Another pair of samples was analyzed to confirm the cause of a narrow transition from a dominance of shadscale with a

mixture of winterfat and Russian thistle to an adjacent stand dominated by mat saltbush and burroweed. The following changes occur within a few feet: decrease in pH from 9.0 to 8.4; increase in conductivity from 0.1 to 1.1; increase in sodium from 54 to 391 ppm; an increase in sulfate from <40 to 565; and a rise in G.S.I. from minimal value to 0.27. This again confirms the greater tolerance of mat saltbush to both sodium and sulfate concentrations.

Finally, a pair of samples was analyzed to illustrate the contrast at a site near Montrose, Colorado, supporting a sparse stand of short, mat saltbush and a near-by depression occupied by a salt slick with a white surface crust, Fig. 35. Between the two samples is a narrow zone of greasewood and saltgrass. Following is the comparison of soils of mat saltbush and the salt slick: pH 8.1 and 8.8; conductivity 2.6 and 9.9; sulfate 1970 and 7000 ppm; G.S.I. 1.36[*] and 1.68[*]; and sodium 1660 and 35,640 ppm!

Comments on Soil Treatments

Much research has been done to discover methods of soil treatment to alleviate the saline or saline-sodic conditions of shale-derived soils. General approaches to soil reclamation have included the addition of nitrogen and phosphate fertilizers, a period of leaching to lower the salinity and conductivity of the soil and soil solution, the addition of a mulch, and often the use of irrigation to insure initial plant establishment (Merino and Crookston 1977, May 1975, Thames and Verma 1977, Aldon 1978, Nielson and Peterson 1973, and Berg and Vogel 1973). Other

approaches have been proposed. Studies have been undertaken to increase the tolerance of plant species to high soil salinity. Pretreatment of wheat seeds with calcium salt solutions decreased the uptake of sodium by the seeds and significantly increased germination (Chandhuri and Wiebe 1968). LaHaye and Epstein (1969) grew 2-week old bean plants in a medium with a concentration of NaCl 1/10 that of seawater. When the calcium, supplied as $CaSO_4$, was maintained in concentrations of 3 mM or greater, the massive movement of sodium across the cell membranes of plant tissue was prevented, and the plants were able to grow.

Recently, researchers have looked at the role microorganisms play in the natural weathering of shales and other rock material. Cundell (1977) discussed bacterial production of polysaccharides which increase soil aggregation. The addition of sulfur to a sodium-saturated montmorillonite soil was found to increase the numbers of Thiobacilli in the soil. The bacteria convert sulfur to sulfuric acid and speed the exchange of calcium for sodium on the clay. Reeder and Berg (1978) found that available forms of nitrogen in Cretaceous shale material as well as added NH_4-nitrogen were apparently taken up by microorganisms and did not remain available for plant use. Nitrifying bacteria were not found to be active in fresh spoil material. Plant uptake of nitrogen on spoil materials did not increase even with the addition of fertilizer nitrogen. Innoculation of spoil material with nitrifying bacteria did not increase plant uptake of nitrogen but the role of various microorganisms in the continual development of soil material is of obvious importance and may be used to speed

the reclamation of shale and spoil.

Calcium sulfate and sulfuric acid have been added to saline and sodic soils to improve texture, tilth, structure of the soil, and absorption of iron (Fletcher and Schurtz 1975; Kelley 1964; Ryan, Stroehlein, and Miyamoto 1975). The addition of calcium allows the divalent ion to out-compete monovalent sodium for adsorption sites on the soil colloids. When a calcium salt is present in the soil, sulfuric acid is effective in liberating the calcium and allowing it to exchange with sodium on the colloid. The substitution of calcium on adsorption sites decreases the dispersion of soil particles and heightens water penetration and soil aeration by flocculating the colloids. The higher available calcium concentration maintains the integrity of the plant cell membrane against a massive influx of sodium.

The addition of soil amendments, such as calcium, sulfate or sulfuric acid, essentially mimics what seems to be the natural weathering pattern of Mancos shale. That is the replacement of adsorbed sodium with adsorbed calcium, and the release of sodium sulfate to the soil solution. Clearly, the addition of gypsum can do no good for soils which already contain an abundance of gypsum. What is required is to hasten the exchange process and in areas of insufficient rainfall to increase the flushing rate of sodium sulfate from the zone of root activity. One possibility of reclamation of reworked Mancos shale would be flooding of an artificially ponded topography followed by periodic drainage to rid the soil of sodium sulfate.

Another growth-inhibiting property of shale-derived soils

is poor aeration resulting from lack of structure due to high sodium content and the fine texture of swelling smectites of the weathered shale. Under field conditions the problem is solved by the admixture of sandstone either as a mantle of broken rock and fragments or the incorporation of weathered sand. This improves aeration, infiltration, drainage, and depth of root penetration. Fragments on the surface function in the manner of desert pavement for "water harvesting" and reduction of soil temperatures. The advantages of this admixture have been demonstrated in uranium-mining reclamation studies in New Mexico (Kelley 1979).

SUMMARY

Within the four-state area of Mancos shale distribution from which samples were obtained, the shale bedrock shows many variations. Texture varies from fine, hard, blocky structure to thin, flaky, friable layers. Interbedded sandstone layers may be present and in some areas weathered eroded fragments of sandstone cap knolls or result in a "desert pavement" effect. Some strata are of the nature of black lacustrine muds. Interbedded throughout the region are deposits of yellowish-white bentonite with high concentrations of sodium. These layers often form a hydrophilic seal across the surface of gently eroded topography. These strata also produce a serious impact on root growth, water relations, soil structure, and chemical inhibitive action. Ratios of illite to smectite vary from 60:40 to 40:60. Exceptions are immediately adjacent to the heat and pressure of intrusives which increase the percentage of illite. A second exception is the composition of layers of bentonite which are nearly all montmorillonite.

Values for pH range from 3.4 in sulfurous shales of low carbonate content to 9.4 in lowland shale-derived soils. The highly acidic soils, although increasing the availability of ions such as copper, iron, manganese, phosphorous, and zinc, are toxic to most vegetation and may be important in reducing oxygen availability for plant growth. At the other end of the pH scale, the alkalinity apparently becomes a selective factor in species distribution.

Concentrations of carbon in the soils of the transects vary from .01% in layers of bentonite or Tropic shale to a maximum of 5.58% in the outwash, shale-derived surface layers of pinyon-juniper. No predictive use of the potential to support a particular kind of vegetation is made of this factor, instead it appears to be an effect of the kind and amount of vegetation growing on the site. Sulfate is rather high in concentration and uniformly distributed within soil profiles both as soluble sodium sulfate and the less soluble calcium sulfate. Because the gypsum saturation indices are so close to unity it is concluded that equilibrium with gypsum is an important control on the salinity of soil waters. Sodium concentrations vary widely, but are usually more concentrated in the subsoils to which sodium sulfate has been leached.

The hypothesis of soil salinity development in Mancos shale-derived soils follows. Pyrite oxidation is the principal source of sulfuric acid which causes acid pH values in shales low in limestone. Where limestone is present, the acid forms calcium sulfate. The gypsum is frequently apparent in crystalline form. When dissolved, an ion exchange equilibrium is reached with sodium-saturated smectite. Some strata are yellow with jarosite, $KFe_3(SO_4)_2(OH)_6$ which results in iron sulfates and reddish iron oxides.

Concentrations of water-soluble sodium in ppm of soil water at field saturation varies in the areas studied for vegetation-soil relationships from 13 ppm to 18,765 ppm and up to 35,640 ppm in a barren salt slick. Mat saltbush is growing in deep layers of

weathered shale having subsurface sodium concentrations of 17,685 ppm!

Within the wide climatic variations of the Colorado Plateau area, the presence on top of knolls of a sandstone layer, a mantle of sandstone fragments, or the addition of weathered sand produces the most mesic vegetation of the area. Such sites in progressively more moist areas support big sagebrush, mountain-mahogany, oak brush, pinyon-juniper, and even ponderosa pine. These soils are non-alkaline, low in sulfates, and low in sodium concentrations.

Where shale-derived soils have been weathered and transported to form alluvium in valleys, good stands of big sagebrush and rich grasslands develop.

Concentrations of sulfate vary with the original chemical composition of the bedrock shale and the degree of leaching. In the frequent downslope sequence of dominance of sagebrush or blackbrush, shadscale, mat saltbush, and greasewood, the sulfate concentration seems to play a specific role. In the transition between shadscale and mat saltbush, there is a marked and rapid increase in sulfate concentration from less than 100 ppm to 1650 ppm. The increase is accompanied by an increase in gypsum saturation index to unity or greater. The growth of galleta grass seems to be inhibited by increased concentrations of soil sulfate.

The principal inhibiting chemical factor is apparently sodium concentration. Its removal is dependent on leaching. The combination of high sodium concentrations and a preponderance of swelling clays (smectite) act together to reduce water infiltration, leaching, and aeration. The shale overburden in strip-mining

is manipulated. It would appear to be imperative to mix into surface layers to be revegetated sandstone rocks, fragments, and weathered sand to correct the above inhibitive effects.

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FIGURES

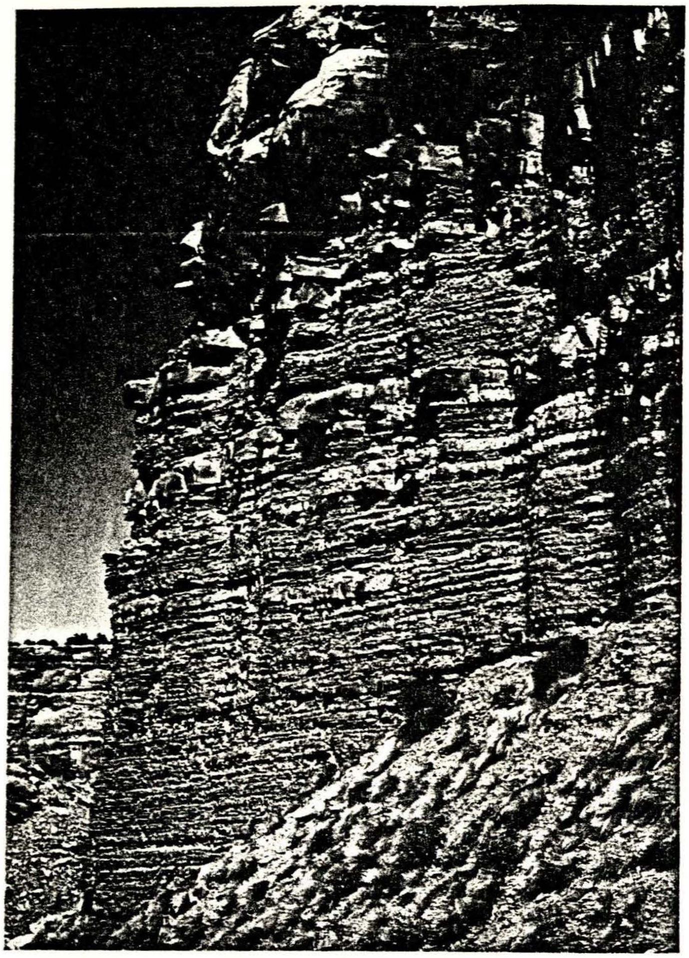


Fig. 2 Upper cliff face of Mesa Verde sandstone; lower cliff face of upper strata of sandy Mancos shale.

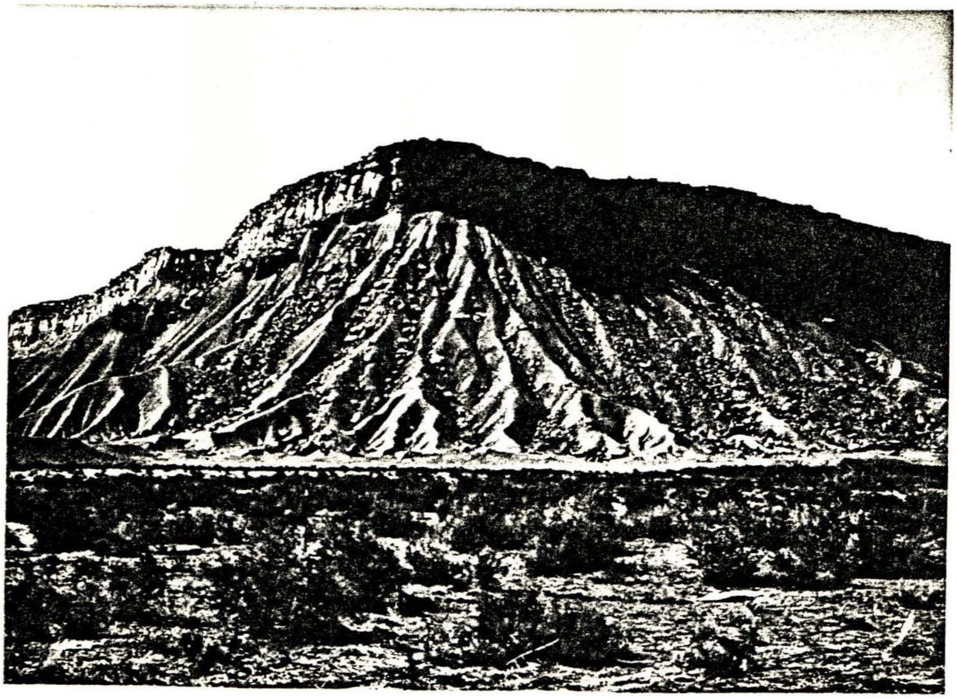


Fig. 3 Silty clay Mancos shale showing typical barreness of vegetation and erosional pattern.

Fig. 4 Interbedded sandstone layers, showing fractures and weathering pattern in underlying Mancos shale.

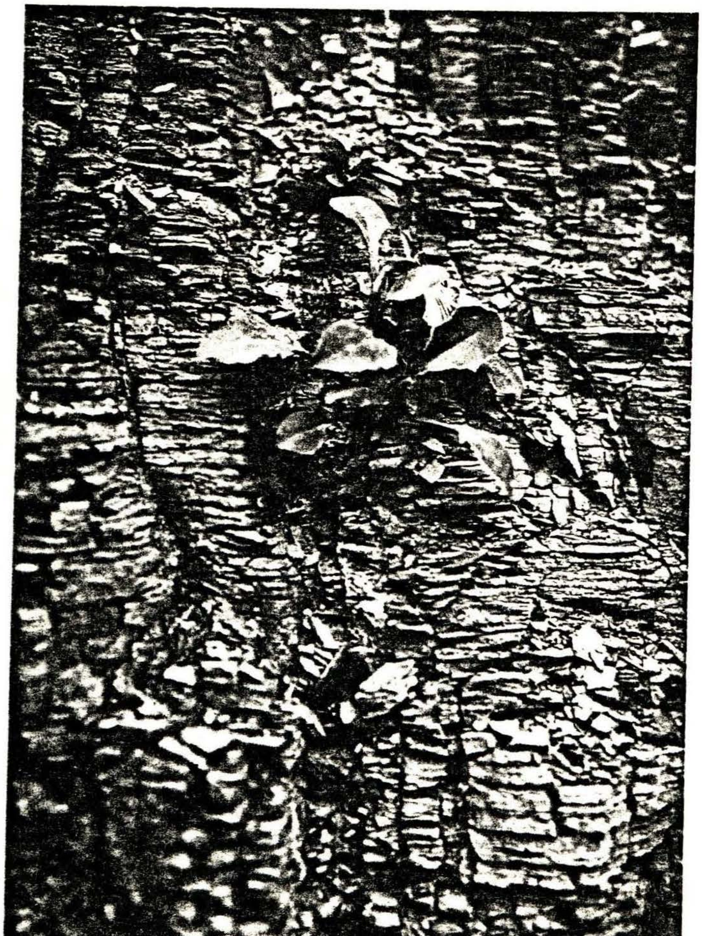


Fig. 5 Contrast of weathered, light-colored bank of shale adjacent to fracture in contrast to dark, grey unweathered shale. Evening-primrose selectively growing in the former.

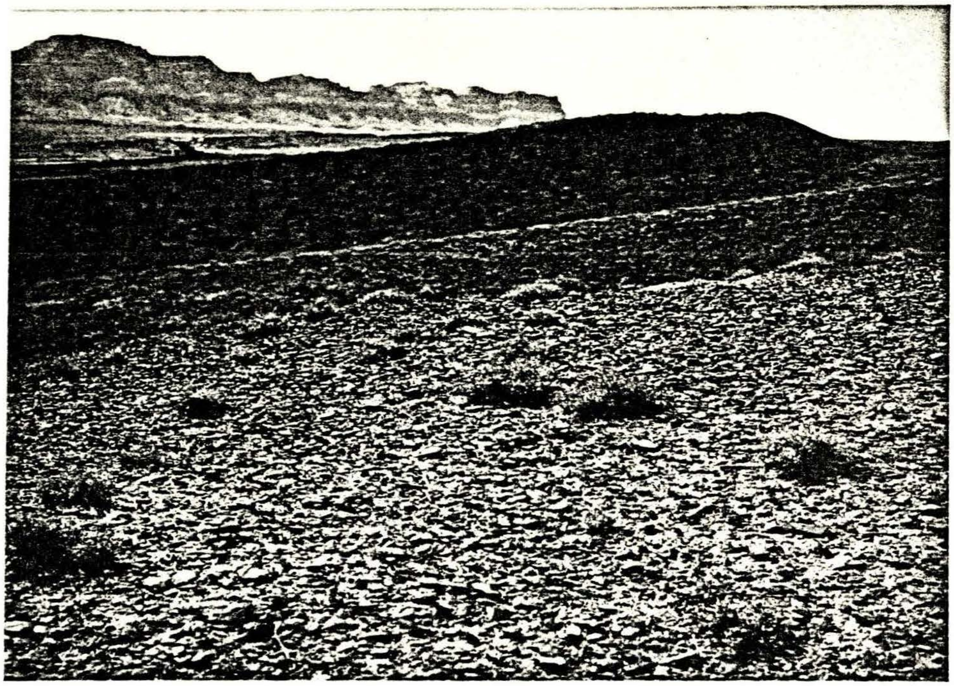


Fig. 6 Mantle of Ferron sandstone fragments across surface of Mancos shale west of Green River, Utah.

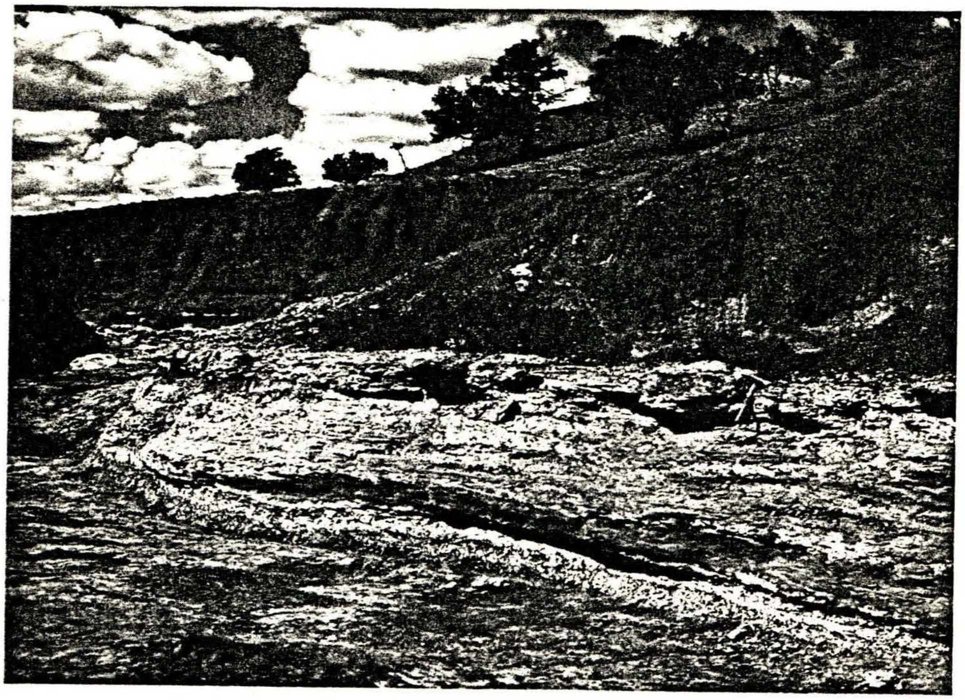


Fig. 7 Contact zone of lower Mancos shale overlying oyster beds at top of Cretaceous Dakota sandstone.

Fig. 8 Strata of lower Mancos of thick, solid, blocky, fine-textured grey shale.

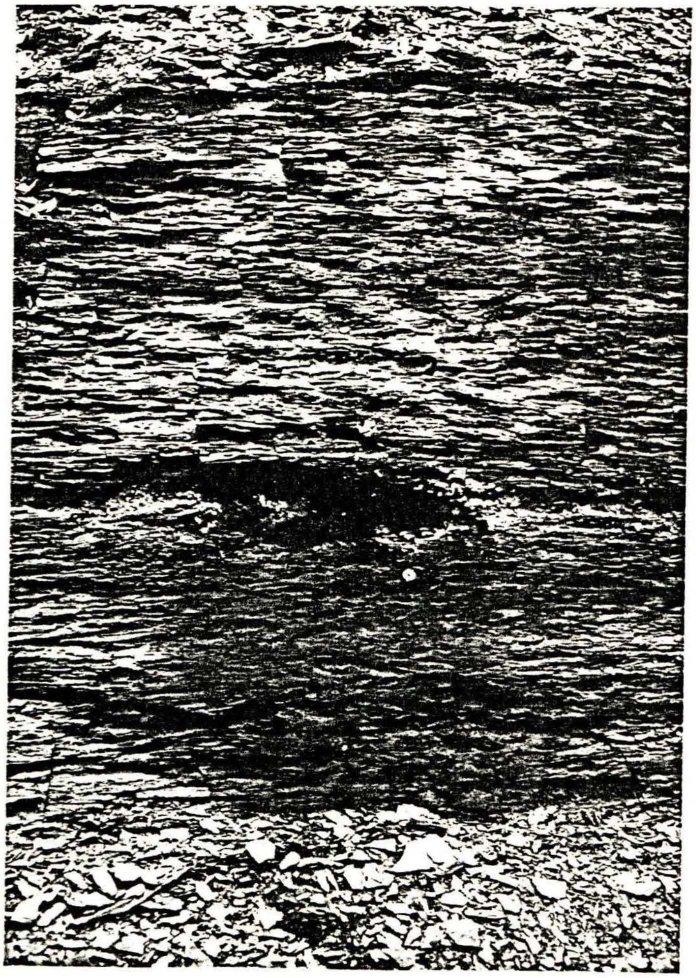


Fig. 9 Thin, platy, and friable Mancos shale.

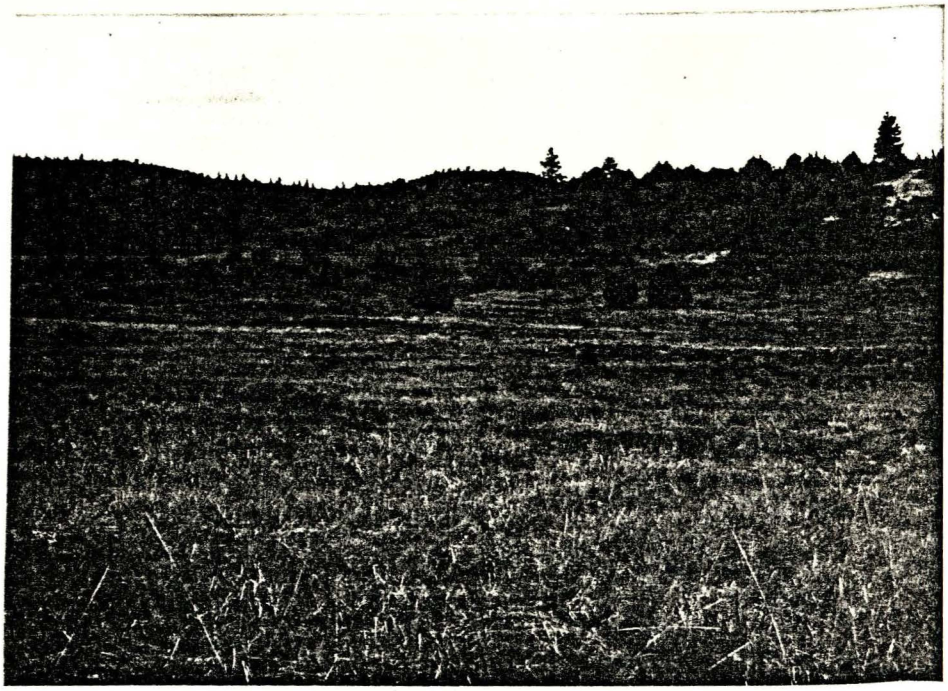


Fig. 10 Mancos shale valley west of Chama, New Mexico.where slopes supported a ponderosa pine forest, now regrowth, pinyon-juniper, and oak. Valley floor is rich grassland.

Fig. 11 Mancos shale north of Dolores, Colorado supporting ponderosa pine, pinyon-juniper, and oak thickets.

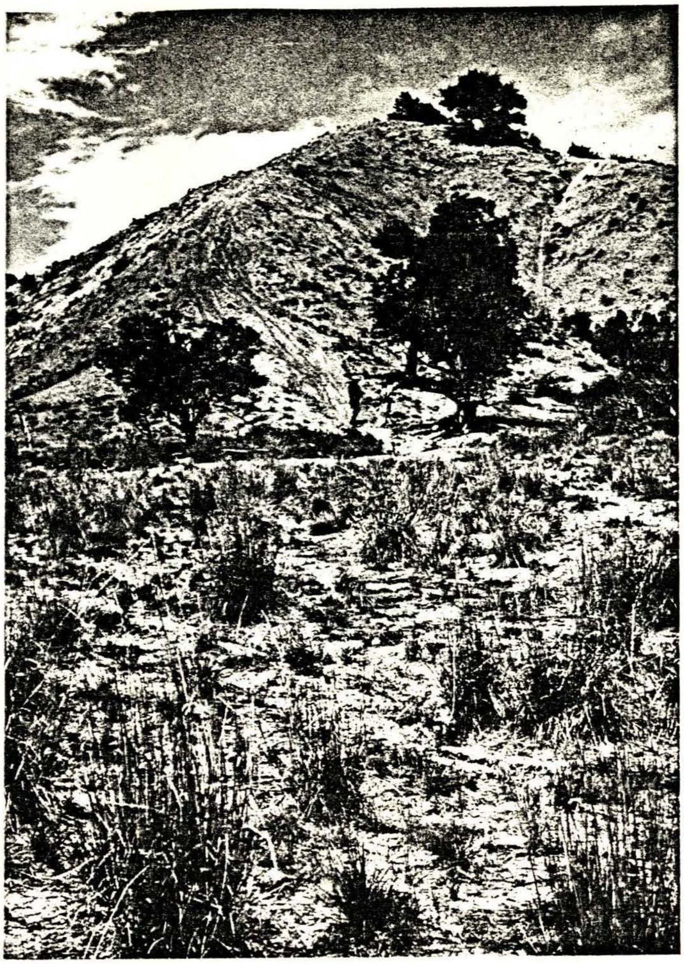


Fig. 12 Scattered Utah junipers on knolls and drainages where presence is related to presence of sandstone fragments and weathered sand.

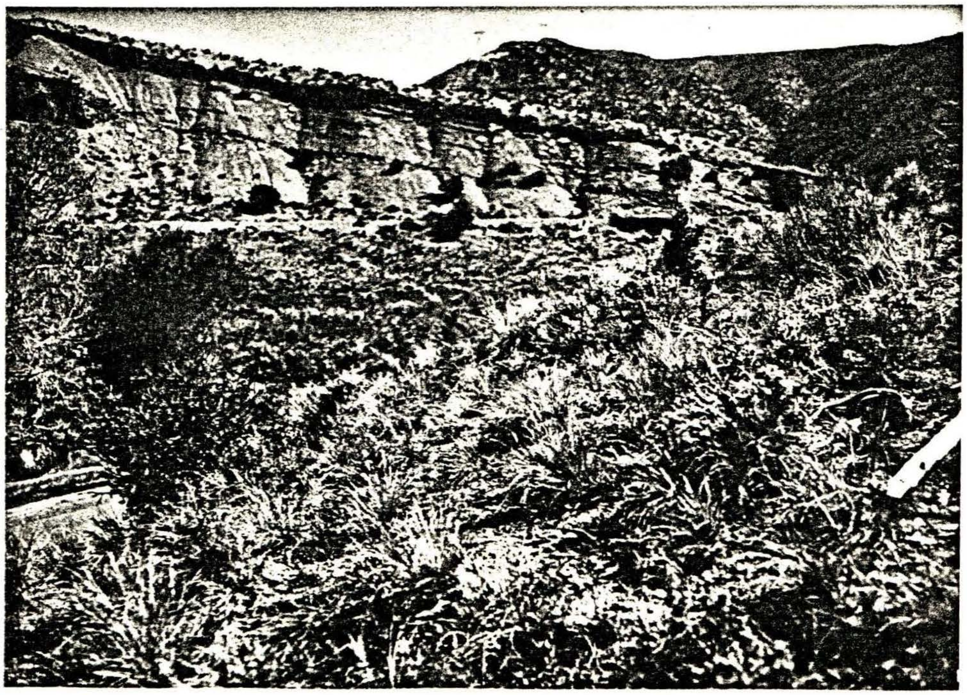


Fig. 13 The upper sandy Mancos shale plus remnants of overlying sandstone near Meeker, Colorado result in relatively rich vegetated slopes dominated by big sagebrush and a fertile valley.

Fig. 14 An extensive sloping plain of Mancos shale with a desert pavement mantle of fragments of sandstone and a vegetation dominated by shadscale.

Fig. 15 Knoll south of Thompson, Utah protected by fragments of sandstone and site of transect down northeast-facing slope on right.

Fig. 16 Mantle of outwash gravel and cobbles over Mancos shale. Mantle allows for improved vegetative growth.

Fig. 17 Mancos shale knoll east of Austin, Colorado which is capped by common yellowish-colored layer of bentonite clay. Site of transects to the left and to the right.

Fig. 18 General view of barren area of Tropic shale which has a high concentration of montmorillonite and high concentrations of sodium.

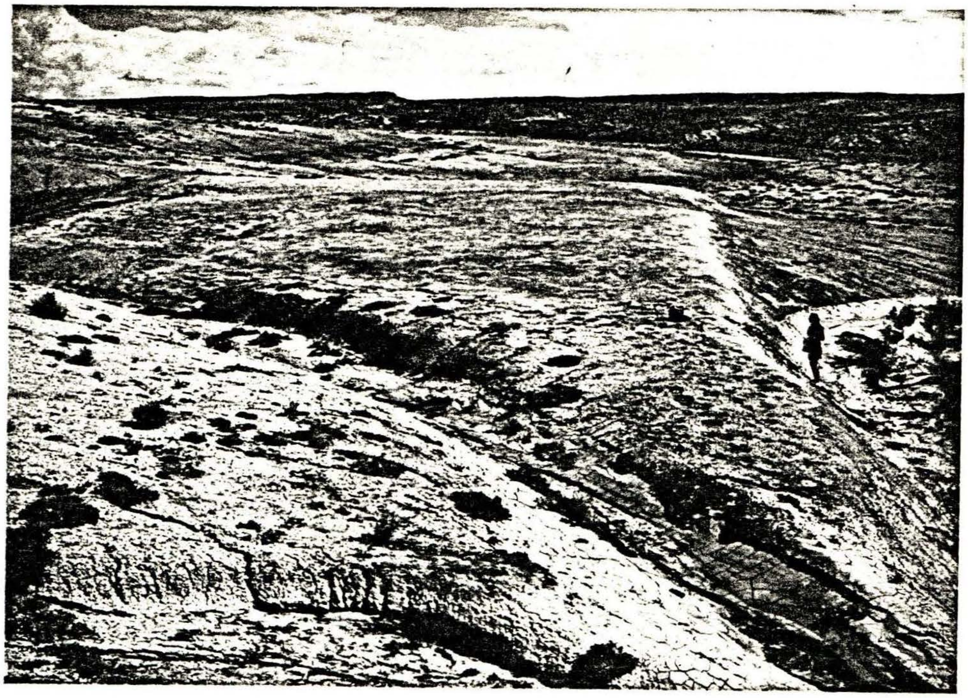


Fig. 19 View of barren triangular area of Tropic shale capped with a foot-thick layer of saline, montmorillonitic bentonite.

Fig. 20 Detail of pit in foot-thick layer of white bentonite overlying Tropic shale.

Fig. 21 Unusual temporal cover of spring flowers on Tropic shale after late winter snows.

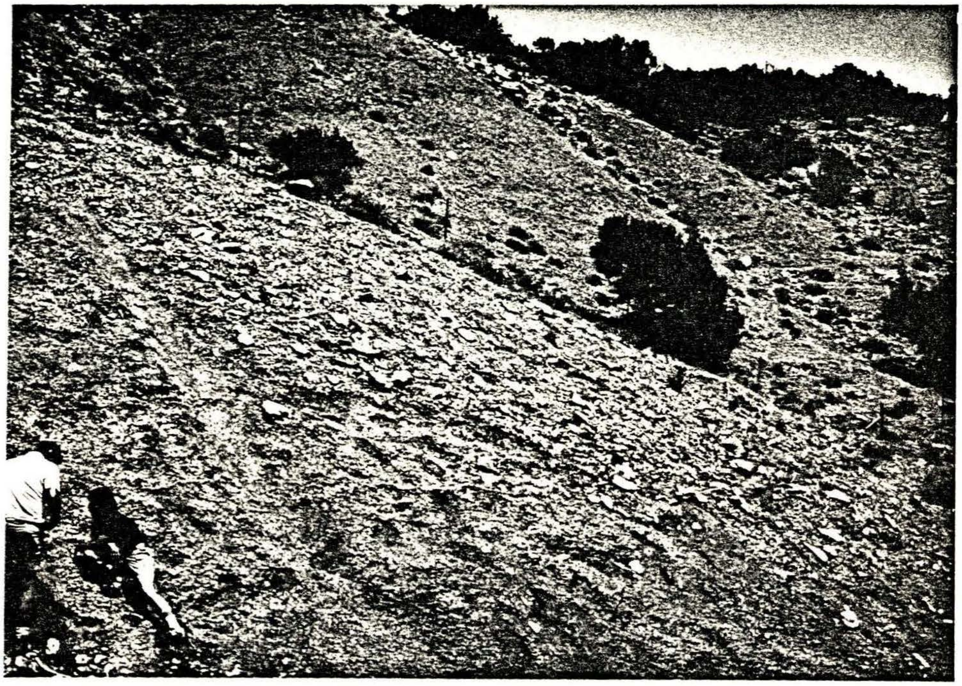


Fig. 22 Growth of Utah juniper under edaphic control where remnants of Mesa Verde sandstone cover upper Mancos shale.

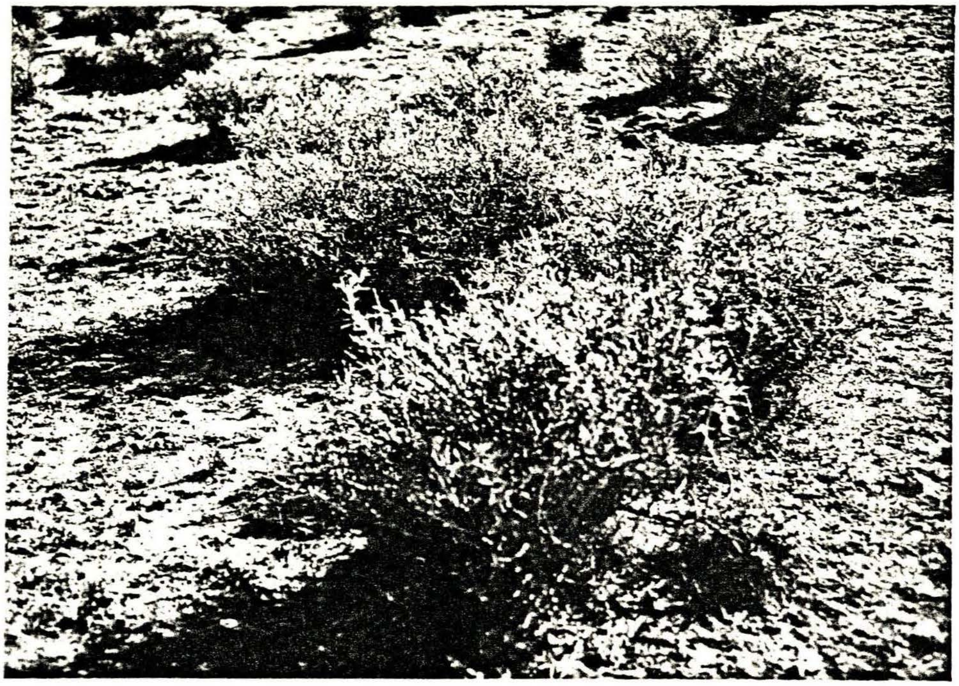


Fig. 23 Black brush vegetation on top of knoll in response to influence of outwash sand and soil depth, north of Loma, Colorado.

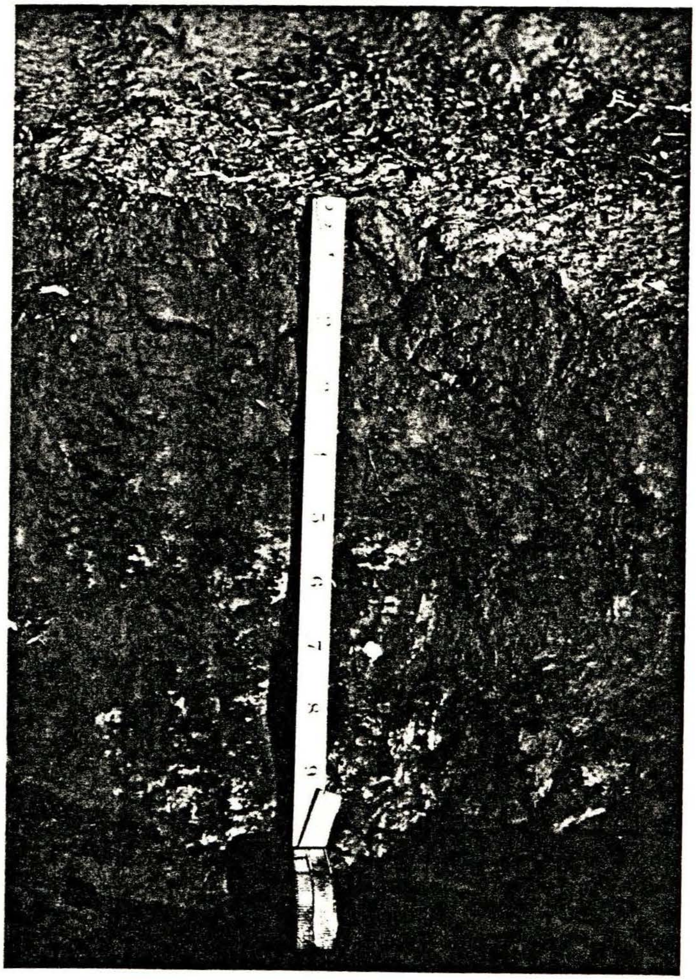


Fig. 24 Soil profile under blackbrush vegetation at top of knoll, north of Loma, Colorado.

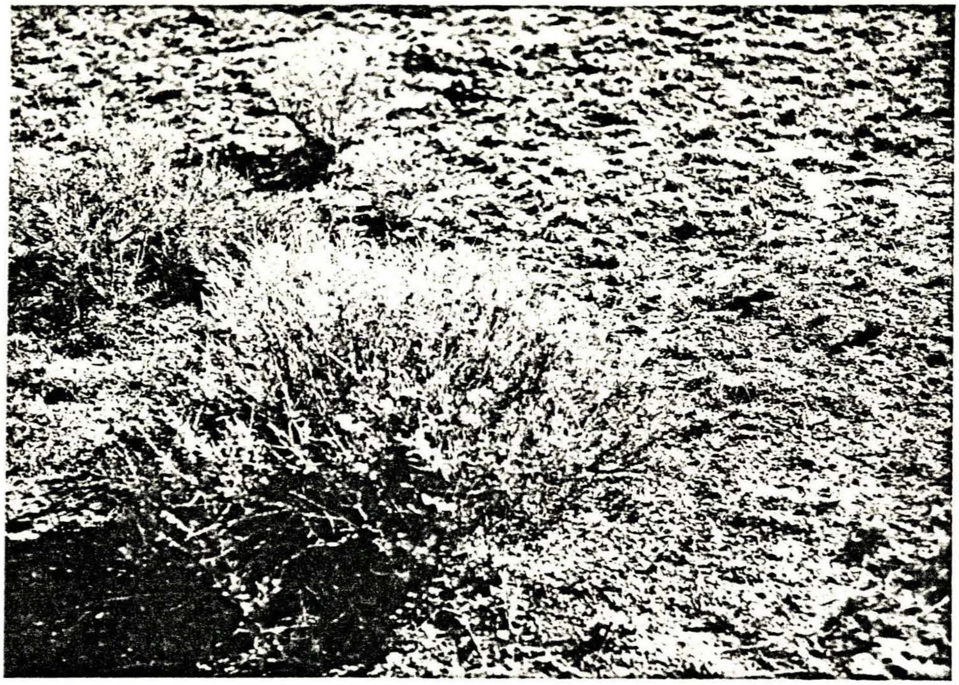


Fig. 25 Vegetation of shadscale and galleta below blackbrush of transect north of Loma, Colorado.

Fig. 26 Soil profile within shadscale-galleta zone, north of Loma, Colorado.

Fig. 27 Vegetation of shadscale-horsebrush zone of transect north of Loma, Colorado.

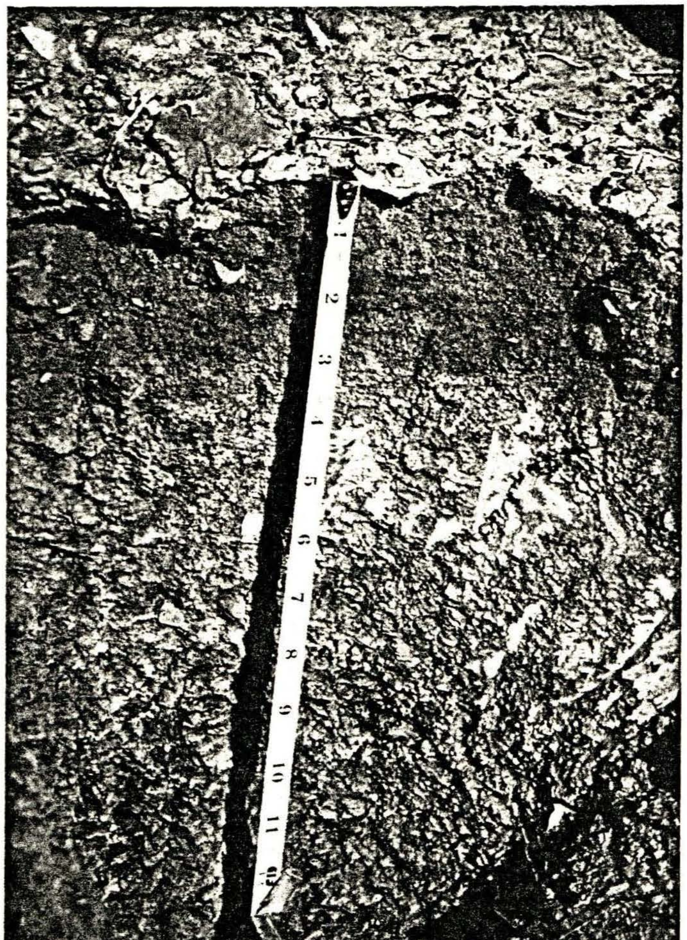


Fig. 28 Soil profile within shadscale-horsebrush zone where there is a deepening soil and caliche layer.

Fig. 29 Vegetation of <u>Atriplex</u> <u>corrugata</u> and horsebrush of transect north of Loma, Colorado.

Fig. 30 Soil profile within <u>Atriplex</u> <u>corrugata</u>-horsebrush zone.

Fig. 31 Vegetation of Atriplex corrugata dominated zone of transect north of Loma, Colorado.

Fig. 32 Soil profile of Atriplex corrugata zone with a narrow band of caliche and iron oxide below.

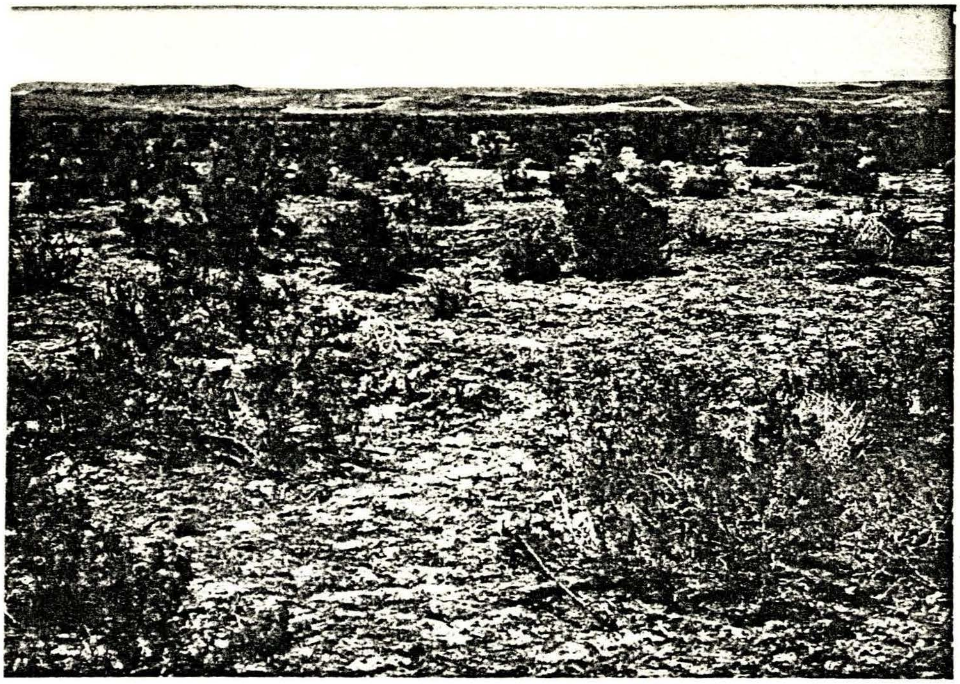


Fig. 33 Vegetation of greasewood zone in lowest area of slope of transect north of Loma, Colorado.

Fig. 34 Typical soil profile of greasewood zone with encrusted light-colored surface, two inches of structureless granular soil over hard, cemented silty subsurface.

Fig. 35 Extreme of salinity resulting in salt flats surrounded by saltgrass and burroweed.

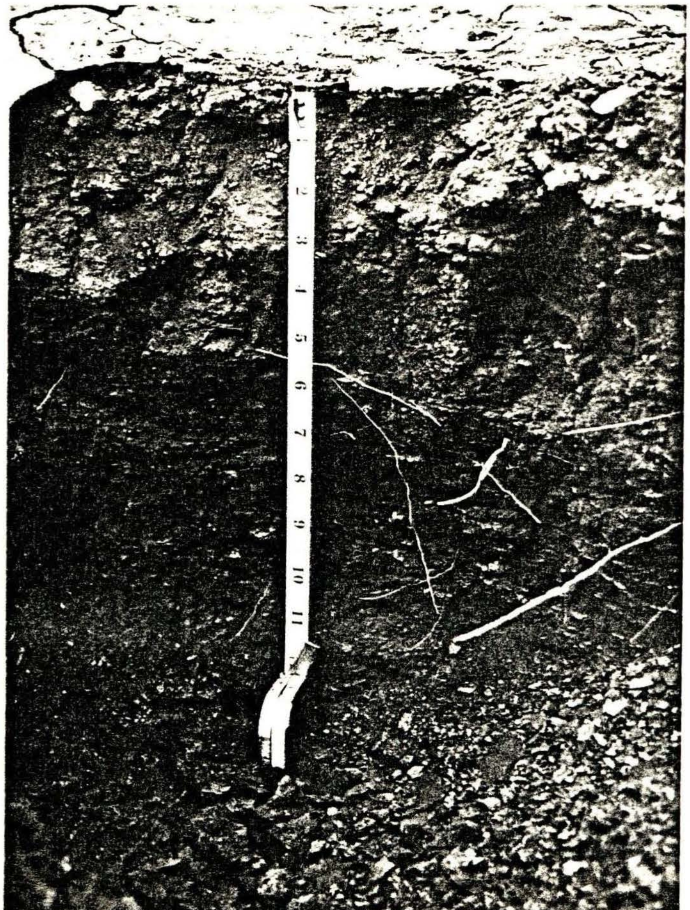


Fig. 36 Soil profile of residual soil weathered in place from the Mancos shale, east of Thompson, Utah.

Fig. 37 Alluvial calcareous soil of weathered, leached Mancos shale showing excellent structure and supporting big sagebrush.

Fig. 38 Mancos shale valley of weathered alluvium in southern Colorado supporting ponderosa pine, pinyon-juniper, and a rich native grassland.

Fig. 39 Slope of Mancos shale at Mancos, Colorado taken from sagebrush on alluvium across pinyon-juniper and barren areas with bands of buckwheat to pinyons on ridge mantled with sandstone.

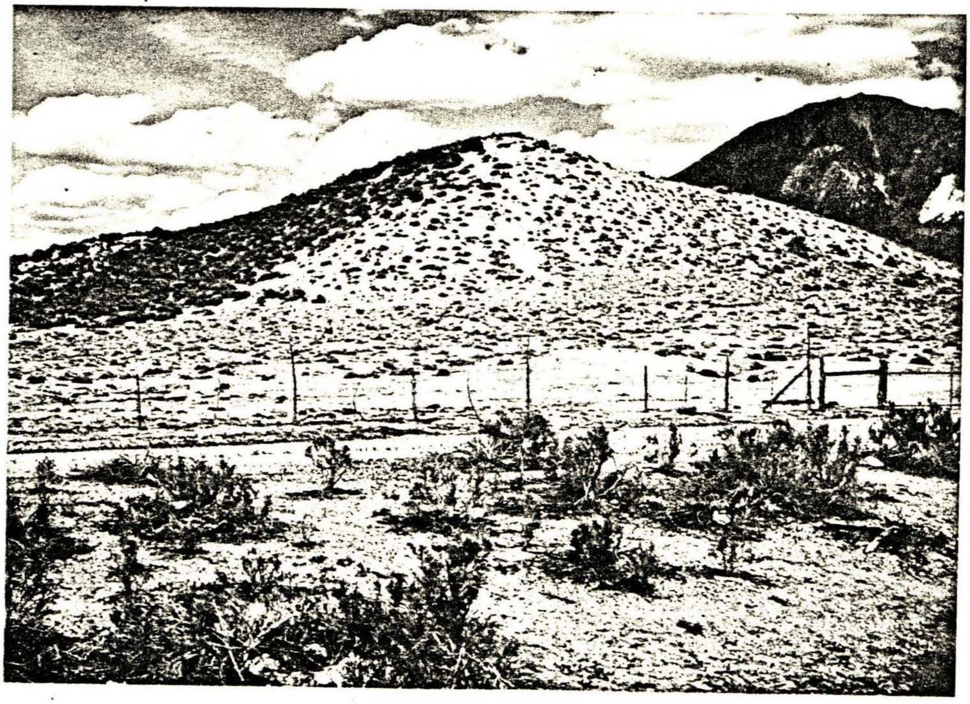
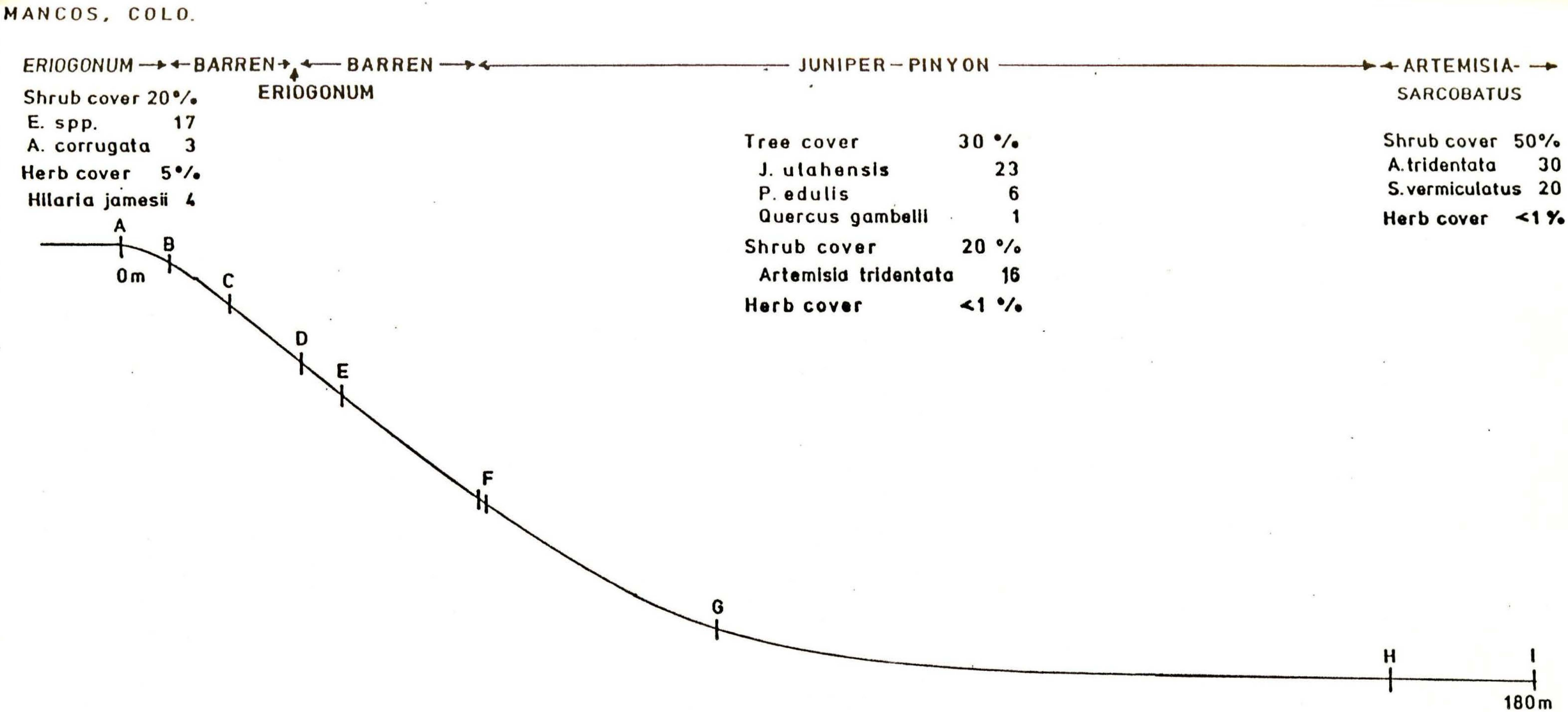


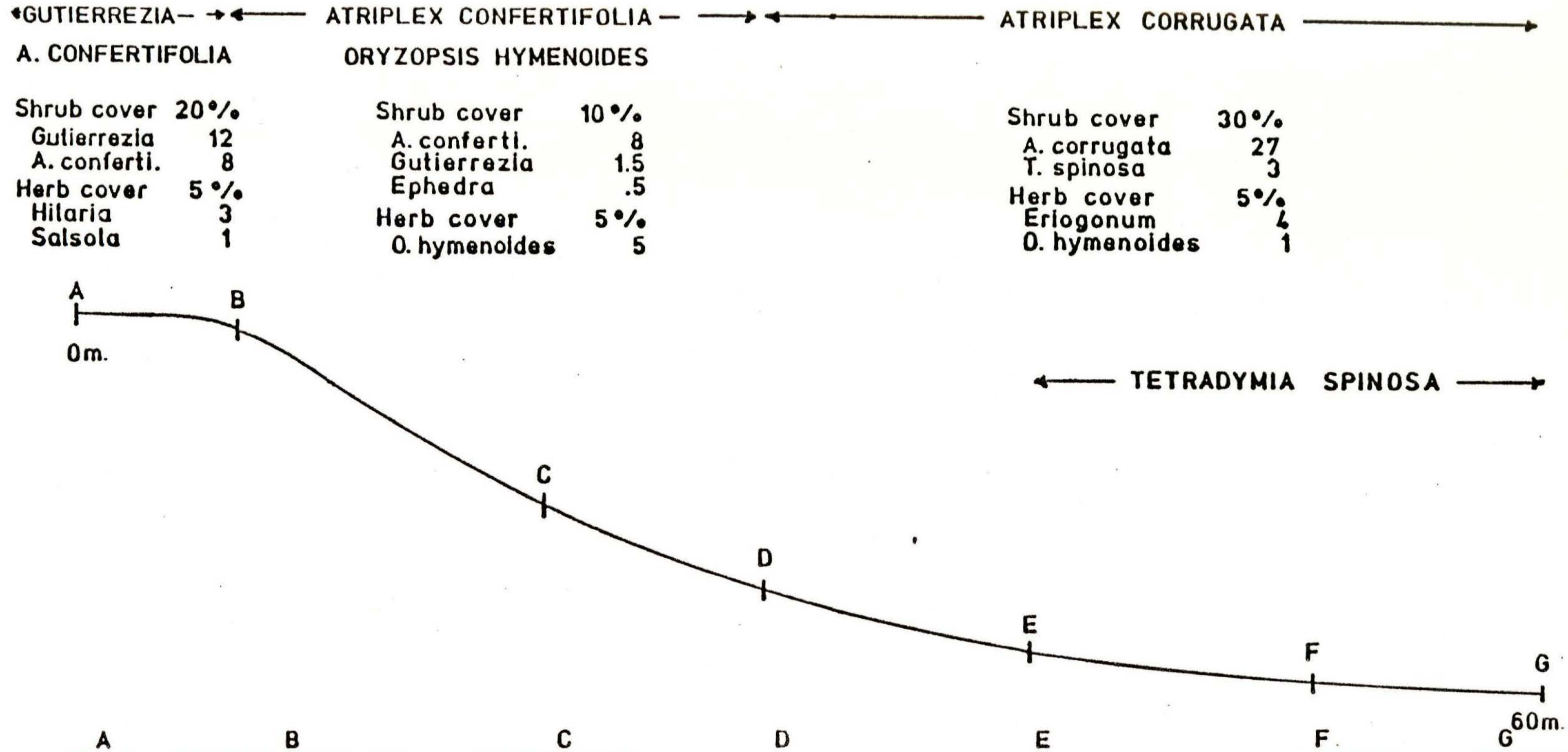
Fig. 40 Slope exposure effect with southwest slope of sparse shadscale and northwest slope of big sagebrush, south of Paonia, Colorado.



	A		B		C		D		E		F		G		H		I	
Depth (in)	0-1	1-3	0-1	2-9	0-1	6-8	0-2	6-8	0-2	6-8	0-4	6-10	0-2	6-8	0-2	6-8	0-2	4-6
Sand/clay (%)					37/33		30/46	31/42			36/41					20/49	23/48	23/50
pH	7.7	7.5	7.4	7.9	4.7	3.4	4.4	3.8	3.8	3.4	7.9	7.6	7.9	8.8	8.3	8.6	8.6	8.4
Cond. (mmhos)	2.4	2.4	2.5	1.0	2.3	.3	2.4	1.4	2.2	2.4	.2	.1	.8	.2		.2	.2	
Carbon (%)	1.53		1.41	2.74	2.07	2.83	2.23	2.16	2.20	2.79	2.45		5.58	3.05	2.41	2.14	2.26	1.78
Sulfate (ppm) (1:5 extract)			1650	425	1300		1250	630	1450									
G.S.I.			1.21	0.20	0.89		0.85	0.34	1.03									
Sodium (ppm) (sat. soil sol'n.)	13	13	13	40	27	40	13	13	27	27	13	13	27	81	121	162	189	108

Fig. 41 Vegetation and soil properties of a Mancos shale slope near Mancos, Colorado.

THOMPSON, UTAH

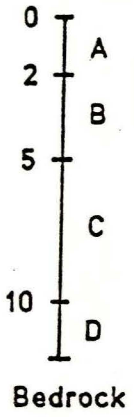


	A	B			C		D		E		F		G	
Depth (in.)	6-8	0-2	2-6	rock	0-3	6-8	0-2	6-8	0-2	6-8	0-2	6-8	0-2	6-8
Sand/clay (%)			11/48	8/51		13/47	11/50		16/40		9/8	10/5		
pH	9.4	8.1	9.1	9.9	8.9	8.4	8.5	8.1	8.1	8.1	8.2	8.2	8.2	8.6
Cond. (mmhos)	.2	2.6	1.7	1.5	.3	1.7	1.1	2.4	2.3	2.6	2.3	2.7	2.4	4.1
Carbon (%)	.28	.26	.16	.15	.19	.21	.27	.30	.46	.46	.67	.65	.51	.57
Sulfate (ppm) (1:5 extract)	<30		825			870		1500		1720		1660		2300
G.S.I.			0.37			0.52		1.07		1.26		1.20		1.44+
Sodium (ppm) (sat. soil sol'n.)	81	513	1633	5926	54	189	27	94	27	216	67	216	148	3861

Fig. 42 Vegetation and soil properties of a Mancos shale slope near Thompson, Utah.

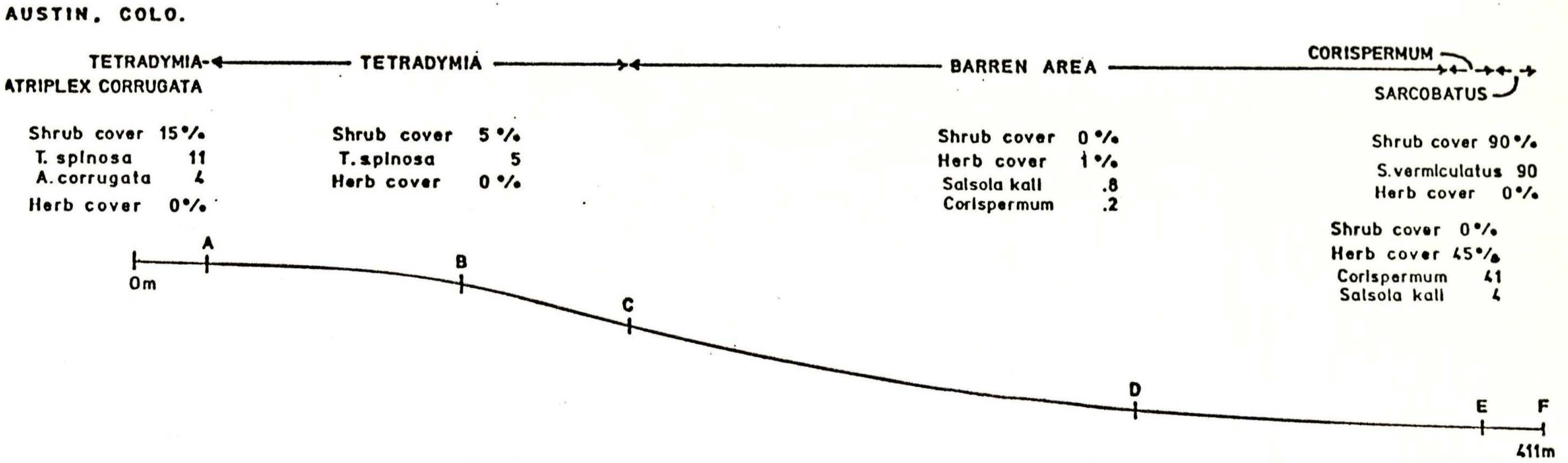
THOMPSON, UTAH

Weathering Profile (in situ)



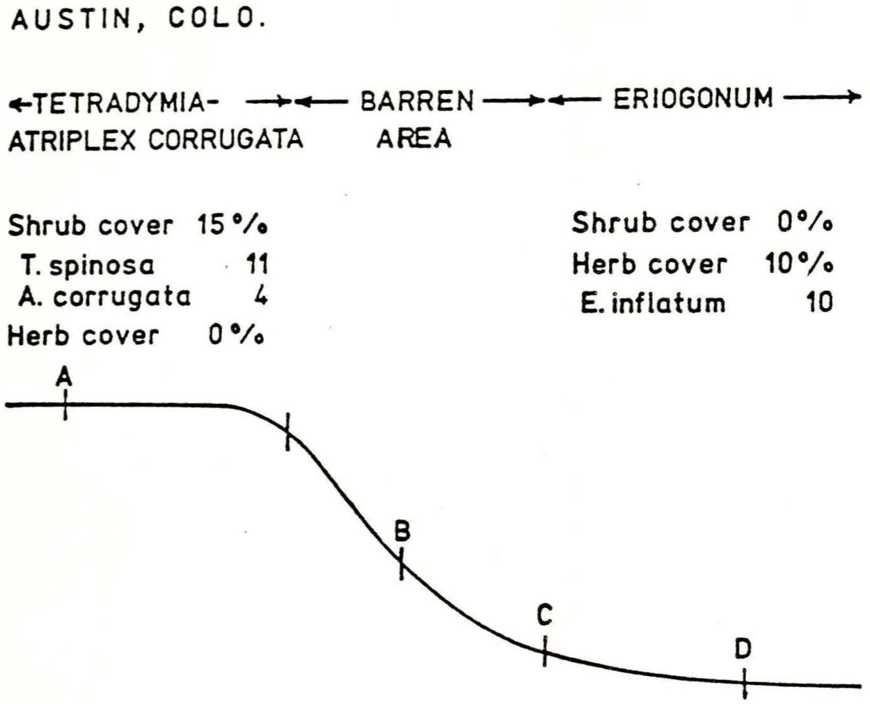
	A	B	C	D
Depth (in)	0-2	2-5	5-10	10-12
Sand/clay (%)		9/4	9/5	
pH	8.0	7.6	8.7	9.1
Cond.(mmhos)	2.5	3.4	5.3	2.9
Carbon (%)	.63	.67	.52	.57
Sulfate (ppm) (1:5 extract)			3500	1375
G. S. I.			2.39^{+}	0.55
Sodium (ppm) (sat. soil sol'n.)	40	2511	5899	4347

Fig. 43 Properties of a soil profile of Mancos shale weathered in place near Thompson, Utah.



	A			B			C			D			E			F		
Depth (in)	0-1	1-10	rock	0-2	6	6-8	0-3	3-5	5-6	0-2	3	5-6	0-2	4	6-10	0-1	1-2	2-4
Sand/Clay (%)	29/44	2/13		24/8	5/13	11/6	34/36	34/49	10/10	21/8		3/10	22/45	29/44	21/5			15/51
pH	8.3	7.8	5.7	8.0	7.0	6.9	8.4	8.5	8.1	7.9	7.7	7.1	8.8		7.9	9.2	8.7	8.8
Cond. (mmhos)	1.9	2.4	2.9	2.5	2.3	2.5	1.0	.5	2.4	2.8	2.6	4.7	.4		2.9	.8	.6	.6
Carbon (%)	.83	.31	.85	.60	.97	.65	.85	.65	.24	.77	.40	.47	.62	.64	.57	1.88	1.56	1.13
Sulfate (ppm) (1:5 extract)		1560				1520			1330		1400	1400		86	1560			
G. S. I.		1.12				1.07			0.92		0.94				0.90			
Sodium (ppm) (sat. soil sol'n)	378	162	553	27	54	243	40	40	40	40	567	3928	135	715	2497	796	594	1228

Fig. 44 Vegetation and soil properties of a Mancos shale slope near Austin, Colorado.



	A			B	C		D	
Depth (in)	0-1	1-10	rock	0-2	0-5	5-8	0-.5	2
Sand/clay (%)	29/44	2/13	rock	rock				
pH	8.3	7.8	5.7	3.7	7.3	5.1	8.0	4.1
Cond. (mmhos)	1.9	2.4	2.9	1.8	2.6	2.5	.8	2.3
Carbon (%)	.83	.31	.85	2.30	.99	2.89	.72	.63
Sulfate (ppm) (1:5 extract)				1210		1810		1560
G. S. I.				0.77		1.35		1.12
Sodium (ppm) (sat. soil sol'n)	378	162	553	526	94	135	54	81

Fig. 45 Vegetation and soil properties of a steep Mancos shale slope near Austin, Colorado.

LOMA, COLO.

← COLEOGYNE-HILARIA → ← ATRIPLEX CONFERTIFOLIA-HILARIA → ← ATRIPLEX CORRUGATA →

← TETRADYMIA →

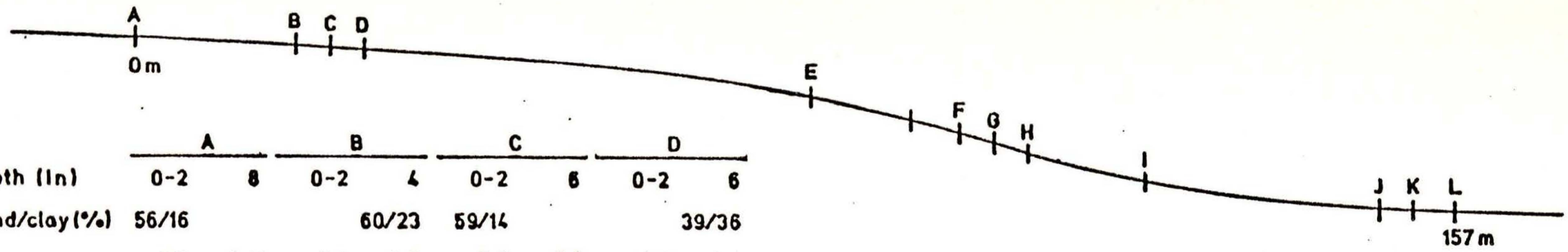
Shrub cover 30%	
C. ramosissima	30
Herb cover	10%
H. jamesii	8
Festuca sp.	2

Shrub cover 25%	
A. confertifolia	25
Herb cover	10%
H. jamesii	9

Shrub cover 25%	
A. confertifolia	14
T. spinosa	11
Herb cover	5%
H. jamesii	5

Shrub cover 30%	
A. corrugata	14
T. spinosa	15
Herb cover	5%
H. jamesii	4

Shrub cover 20%	
A. corrugata	19
T. spinosa	1
Herb cover	<1%
H. jamesii	<1

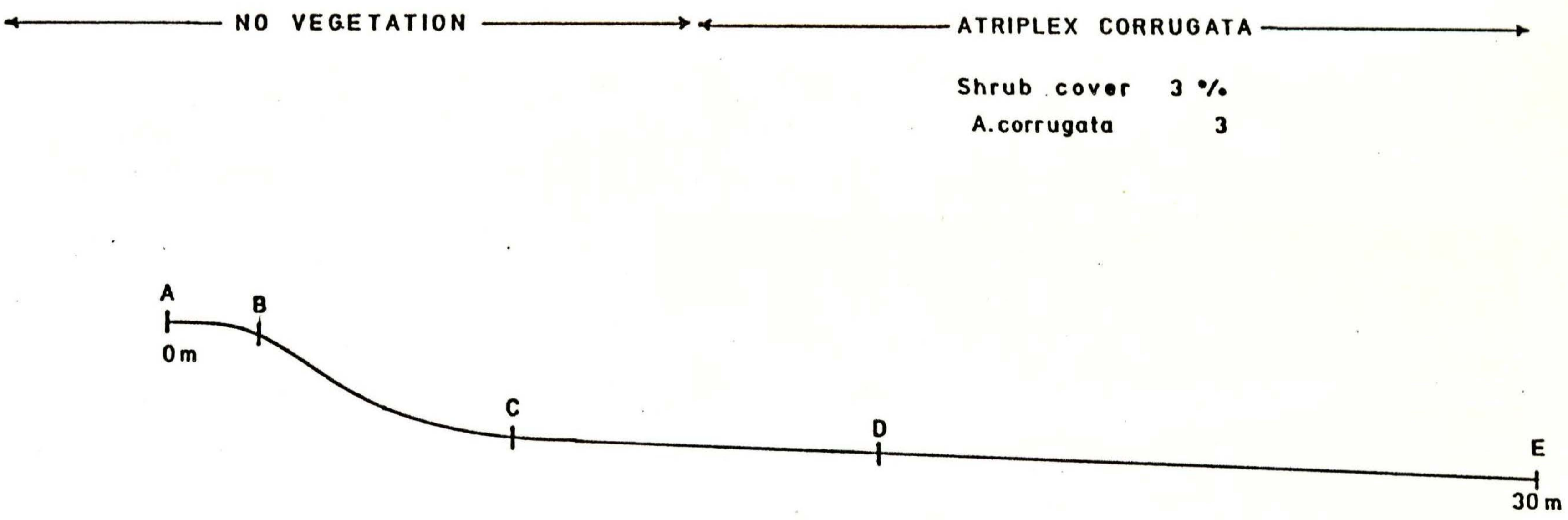


	A		B		C		D	
Depth (in)	0-2	8	0-2	4	0-2	6	0-2	6
Sand/clay (%)	56/16			60/23	59/14			39/36
pH	8.3	8.5	8.8	8.9	8.8	9.1	8.9	9.4
Cond. (mmhos)	.2	.1	.4	.2	.2	.2	.2	.2
Carbon (%)	.71	.45	.72	.52	6.9	.44	.50	.54
Sulfate (ppm) (1:5 extract)	<30		<30	<30	<30	<30		
G. S. I.								
Sodium (ppm)	<13	27	27	13	13	202	27	229

	E		F		G		H		I		J		K		L	
Depth (in)	0-2	6-8	0-2	6-8	0-3	7	0-2	5	0-2	6	0-2	4	0-2	3-4	0-2	5
Sand/clay (%)	62/12	55/24		9/52	7/50	10/51	28/39		11/41		12/49	4/85			9/49	4/9
pH	8.9	9.1	9.1	9.1	9.0	7.8	9.1	8.0	8.0	7.8	8.9	8.2	8.2	8.1	8.1	8.4
Cond. (mmhos)	.3	.2	.2	.1	.1	2.5	.3	2.3	2.3	2.3	.3	2.7	2.3	2.2	2.4	3.1
Carbon (%)	.44	.46	.42	.25	.36	.36	.89	.35	.37	.30	.44	.53	.44	.39	.37	.41
Sulfate (ppm) (1:5 extract)	<30	<30	<30	~30		1650	~40	1400	1300	1300	~40	2080	1200	1750	1520	2900
G. S. I.						1.21		0.98	0.89	1.07		1.59+	0.81	1.29	1.17	2.37+
Sodium (ppm) (sat. soil sol'n.)	27	27	27	54	27	81	54	81	13	27	67	351	13	108	121	553

Fig. 46 Vegetation and soil properties of a Mancos shale slope near Loma, Colorado.

PARIA, UTAH (Tropic shale)



	A			B		C		D		E	
Depth (in.)	0-1	4	12	0-1	6	0-1	6-8	0-1	6-8	0-1	6-8
Sand/clay (%)		0/100	7/56	7/56		9/59		7/68		8/61	6/74
pH	8.5	9.5	7.5	8.7	9.7	8.0	8.9	9.0	8.3	8.1	9.1
Cond. (mmhos)				3.1	2.5	2.6		1.2	6.2	2.8	7.5
Carbon (%)	.13	.09	.01	1.09	1.19	.50	.56	.50	.44	.32	.30
Sulfate (ppm) (1:5 extract)				1300	500	1600	5500		3500	1860	4350
G.S.I.						1.04	2.74+		2.13+	1.17+	1.67+
Sodium (ppm) (sat. soil sol'n)	17550		13	8235	7897	1417	18765	4036	8032	2524	17685

Fig. 47 Vegetation and soil properties of a Tropic shale slope east of the Paria River between Page, Arizona and Kanab, Utah.

Fig. 48 Thin, platy shale coated with yellow sulfurous compounds (jarosite) which when wet become very acidic.

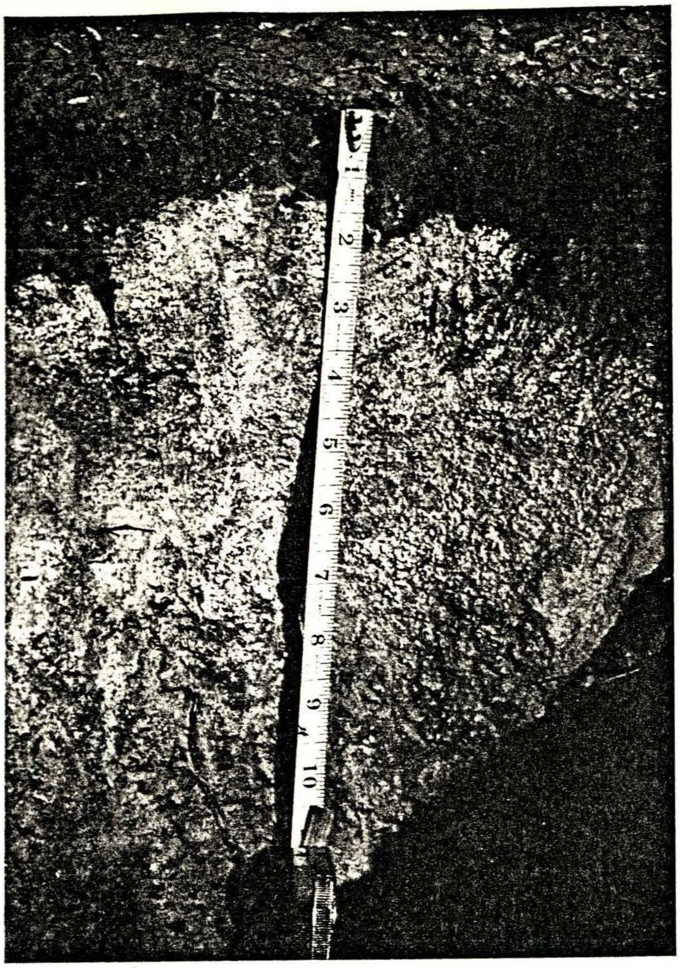


Fig. 49 Soil profile of top of knoll of transect east of Austin, Colorado with a sodium-rich powdery surface soil.

Fig. 50 Sharp transition from barren area across narrow zone of bugseed to greasewood at lower end of transect east of Austin, Colorado.